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Volume Two **Number Four**

SCHOOL OF MINES AND METALLURGY

UNIVERSITY OF MISSOURI

BULLETIN

MAY, 1916

TECHNICAL SERIES

GEOLOGIC CRITERIA FOR DETERMINING THE STRUCTURAL POSITION OF SEDIMENTARY BEDS

ROLLA, MO.

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SCHOOL OF MINES AND METALLURGY

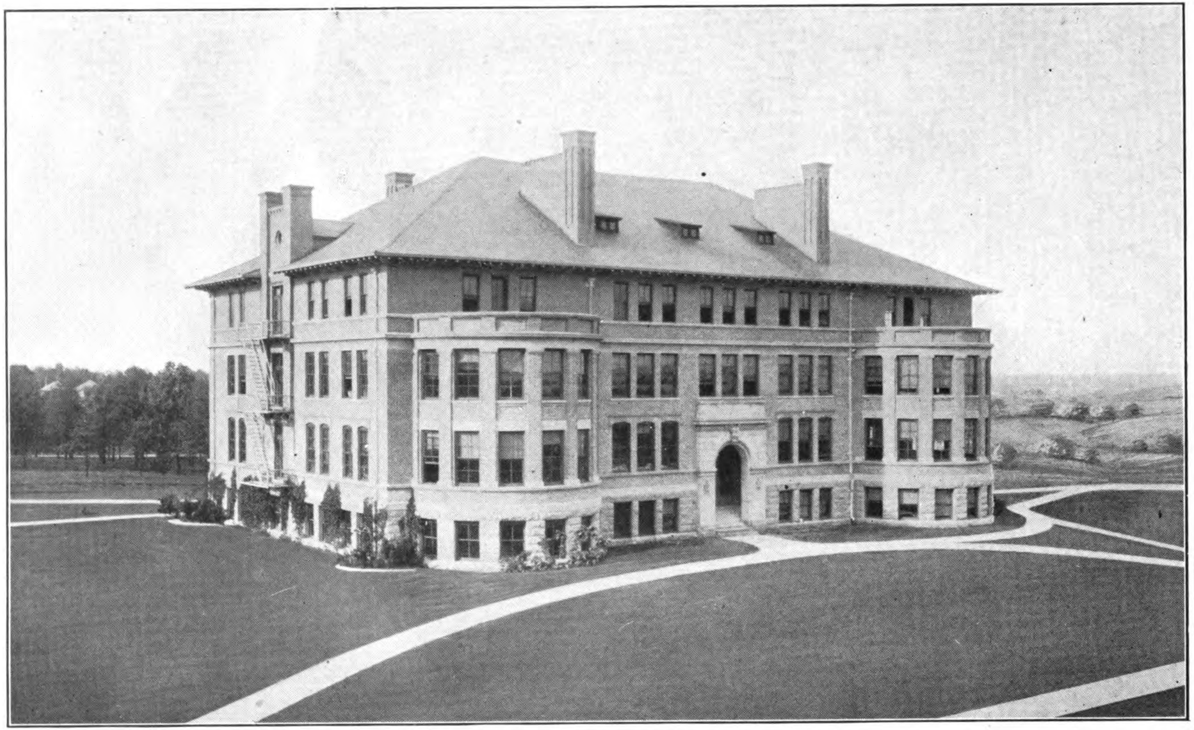
UNIVERSITY OF MISSOURI

GEOLOGICAL CRITERIA FOR DETERMINING THE STRUCTURAL POSITION OF SEDIMENTARY BEDS

BY

G. H. COX, Professor of Geology and Mineralogy, and
C. L. DAKE, Assistant Professor of Geology and Mineralogy

ROLLA, MISSOURI
1916



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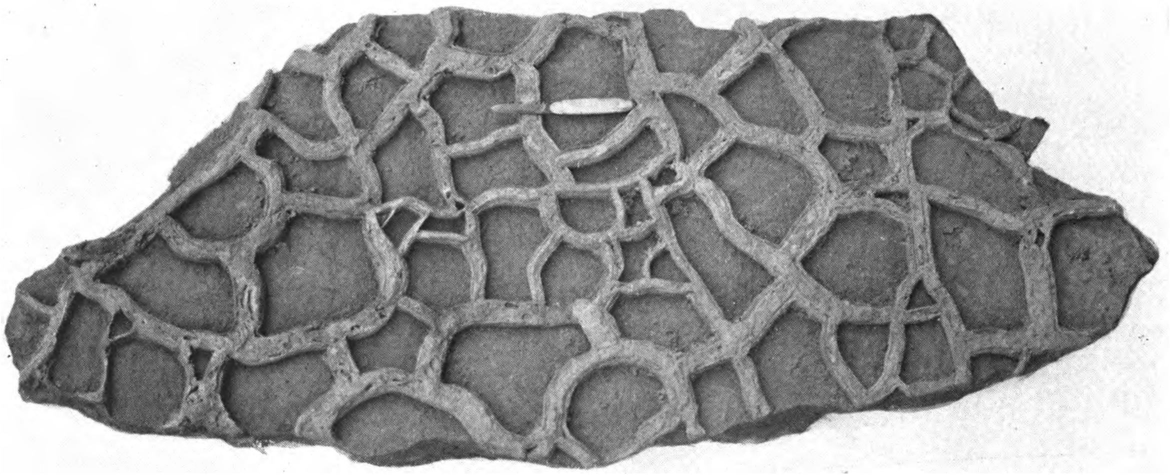

PLATE I.

Limited type of mud cracks adhering to the overlying (younger) bed. From Roubidoux sandstone, Rolla, Mo.

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Introduction.

In presenting the following bulletin to the public the authors have in mind chiefly the bringing together of evidence that can be used in the determination of whether or not a given formation is overturned, and its presentation in a simple, comprehensive form. Although a large portion of this material has been used by various geologists, only small part of it has ever been published. The shallow-water formations of the Ozarks have offered unusual opportunities for study and have presented much that is different from what is usually described under the following headings. So far as known, credit has been given for priority of use, but this should not be taken as final, for it is evident that many of these criteria have been worked out independently by different geologists. Credit is due Edward Kahlbaum for most of the photographic work connected with the preparation of the plates and figures used.

BULLETIN
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School of Mines and Metallurgy
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Vol. II MAY, 1916 No. 4

GEOLOGIC CRITERIA FOR DETERMINING THE STRUCTURAL POSITION OF BEDS.

Ripple Marks.

Ripple marks may be defined as rhythmic undulations that may be seen in sediments, clouds and snow; the name calling attention to the similarity of these markings to ripples formed on the surface of water by the wind. The name refers, then, only to their general shape and repetition and should bear no inference as to size, relative dimensions and origin.

In all cases such wavelike forms have resulted from either translational or undulatory movements in the adjacent medium, the former usually being called "current" ripples and the latter "wave, normal, or oscillation" ripples. A medium which has an oscillatory movement may also have one of translation; consequently it is not uncommon for ripple marks to result from a combination of these two methods (Pl. IV-B) and all gradations from one to the other may be expected. Ripple marks may be formed either by an unequal deposition of new sediments or by the reworking of unconsolidated material previously deposited.

Current Ripple Marks.

"A current of water flowing over a bed of sand reacts on any prominence of the bed. An eddy or vortex is created in the lee of the prominence, and the return current of this vortex checks traveling particles, causing a growth of the prominence on its downstream side. At the same time the upstream side is eroded, and the prominence thus travels downstream. It is a subaqueous dune."* (Figs. 1 and 4.)

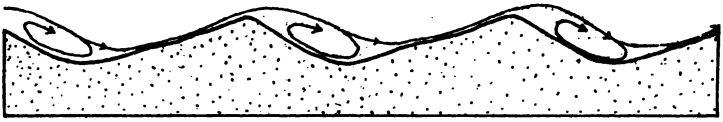

Fig. 1.

Profile of current ripple marks from the Roubidoux sandstone, Rolla, Mo. Actual size. Line with arrows shows direction of movement of current and eddies.

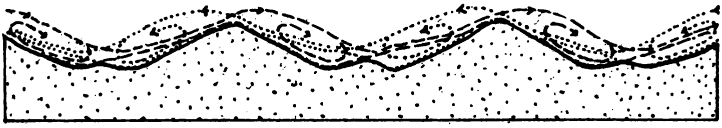

Fig. 2.

Ideal profile of wave ripple marks produced by the superposition of figure 1 upon itself in reversed position.

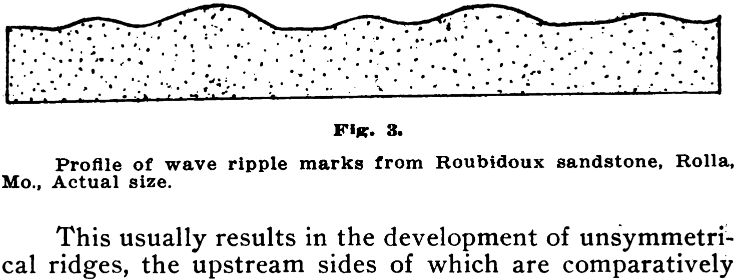

Fig. 3.

Profile of wave ripple marks from Roubidoux sandstone, Rolla, Mo., Actual size.

This usually results in the development of unsymmetrical ridges, the upstream sides of which are comparatively long and gentle, and the downstream slopes short and steep. Such ripple marks are characterized by many irregularities in shape, size, relative dimensions and pattern. The troughs coalescing frequently make many short, discontinuous ridges and an irregular pattern. In general the crests and troughs are quite similar and unsymmetrical. (See Plates II and III.)

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*Gilbert, G. K., Bull. Geol. Soc. America, Vol. X, pp. 135-139.

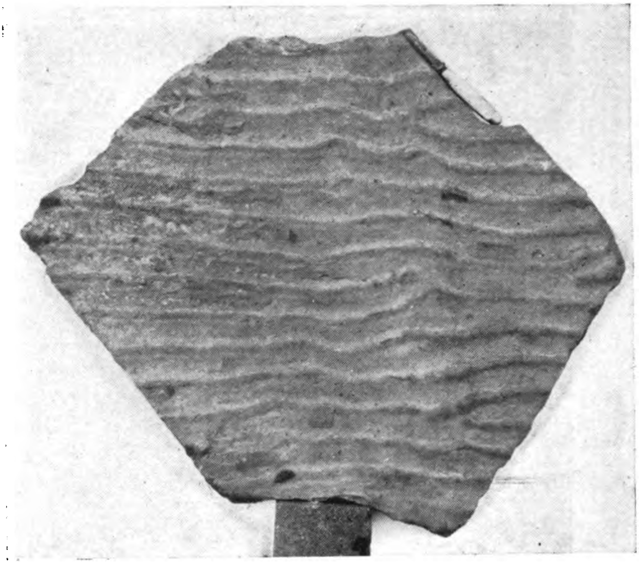

PLATE II-A.
Current ripple marks from Roubidoux sandstone, Rolla, Mo.

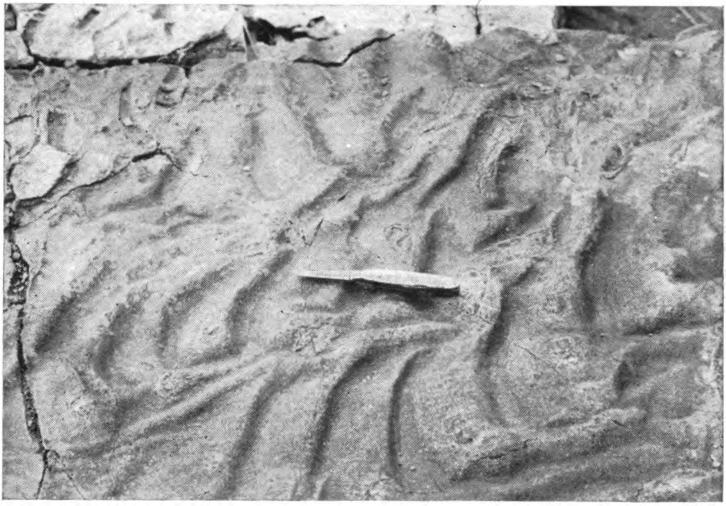

PLATE II-B.
Irregular current ripple marks characteristic of river bars and near shore conditions. From Roubidoux sandstone, Rolla, Mo.

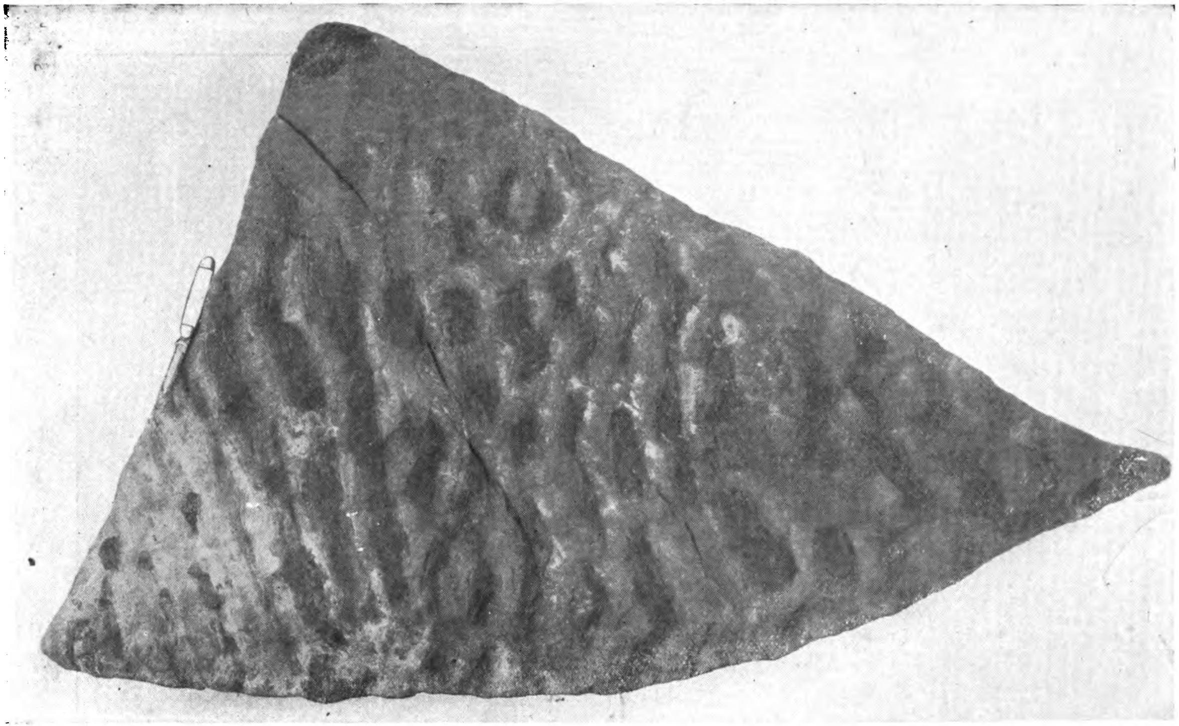

PLATE III.

Current ripple marks, probably formed by rapidly and irregularly flowing currents, such as occur on river bars and on the beach at ebb tide. From Roubidoux sandstone, Rolla, Mo.

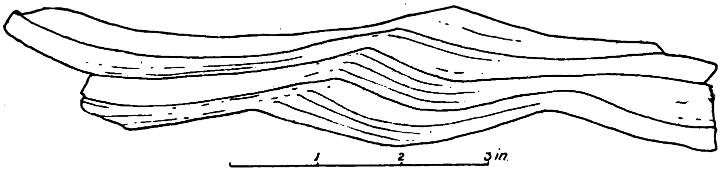

Fig. 4.

Section of current ripple marks showing general shape and result of migration of surface form. From Triassic shale beds of Connecticut Valley (?).

The distance from crest to crest and the ratio of width to depth vary greatly. Larger current ripple marks may have smaller wave ripple marks superimposed upon them.

Water movements are more common and pronounced near the surface than at depth, so that their records should be characteristic of shallow water deposits; but as currents can exist at any depth, current ripple marks can be formed in all kinds of sedimentary rocks. It is noted that current ripples in sandstones are almost always small, only an inch or two from crest to crest, although much larger ones do occur; while those found in limestones are usually a number of feet from crest to crest, although small ones are also found. Some of the examples shown below have been described as wave ripple marks, but their irregularity of shape and pattern, together with the depth at which some of them were shown to have been formed, indicate that they are current ripple marks.

	Width in.	Depth in.	Width/ Depth
Roubidoux sandstone (Ordovician).....	1.6	.2	8.
Roubidoux sandstone (Ordovician).....	2.8	.5	5.6
Trenton limestone[1].....................	9.	1.	9.
Trenton limestone[1].....................	15.	3.	5.
Clinton limestone[1].....................	18.	2.	9.
Springfield limestone[1].................	22.	4.	5.5
Blue limestone[1] [2].......................	24.	2.	12.
Trenton limestone[1].....................	24.	4.	6.
Clinton limestone[1].....................	30.	4.	7.5
Trenton limestone[1] [3]....................	30.	6.	5.
Blue limestone[1] [2].......................	36.	3.	12.
Springfield limestone[1].................	45.	4.5	10.
Silurian limestone[1].....................	49.	3.5	14.
Trenton limestone[1].....................	56.	7.	8.

---

1. Kindle, E. M., Jour. of Geol., 22, 1914, pp. 703-713.
2. Formed in deep water.
3. Formed at a depth of about 200 fathoms.

Cornish* reports that the smallest distance from crest to crest of tidal ripple marks is about 3 feet, that distances of 20 feet are common, and that the average distance of 15 consecutive waves on the sand dunes of the Severn was 37 feet 8½ inches, with an amplitude of about 1 foot 10½ inches. This gives a width-depth ratio of 20 to 1, but the ratio may be as low as 14 to 1.

The chief variations which effect the dimensions of current ripples appear to be the velocity of the current and the size and specific gravity of the particles concerned. The common occurrence of large ripple marks in limestone indicates that the width increases with depth and with the size of the grain, but the general laws are yet to be worked out.

It is evident that such markings may be formed at any depth at which currents exist, and that upon the one hand they grade into the oscillatory or wave-made ripple marks, and upon the other into submarine scours and unconformities.

Wave, Normal, or Oscillatory Ripple Marks.

According to Gilbert** these are produced "By the to-and-fro motion of the water, occasioned by the passage of wind waves. During the passage of a wave each particle of water near the surface rises, moves forward, descends, and moves back, describing an orbit which is approximately circular. The orbital motion is communicated downward, with gradually diminishing amplitude. Unless the water is deep the orbits below the surface are ellipses, the longer axis being horizontal, and close to the bottom the ellipses are nearly flat, so that the water merely swings forward and back. It is in the oscillating current, periodically reversed, that the sand ripples are formed. A prominence occasions vortices alternating on its two sides, and is thereby developed in a systematic way, with equal slopes and a sharp apex. There is a strong tendency to produce the mole laterally into a ridge, the space between ridges is definitely limited by the interference of vortices, and in time there results a regular pattern of parallel ridges equally spaced."

Such ripple marks are characterized by symmetrical ridges and troughs and a very regular pattern. The crests

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*Cornish, Vaughan. The Scottish Geographical Magazine, 17, 1901.

**Op. cit.

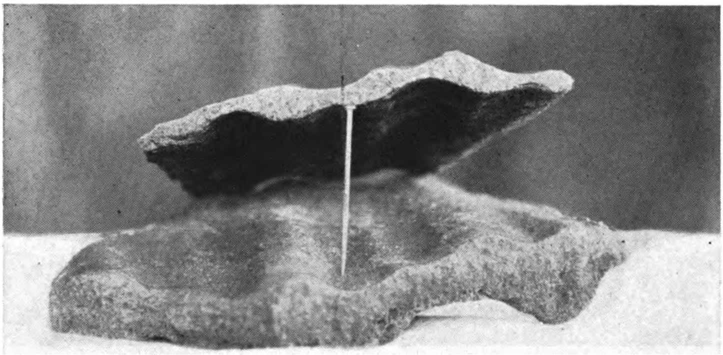

PLATE IV-A.

Mould and cast of wave ripple marks, showing well-developed minor crests. Actual size. From Roubidoux sandstone, Rolla, Mo.

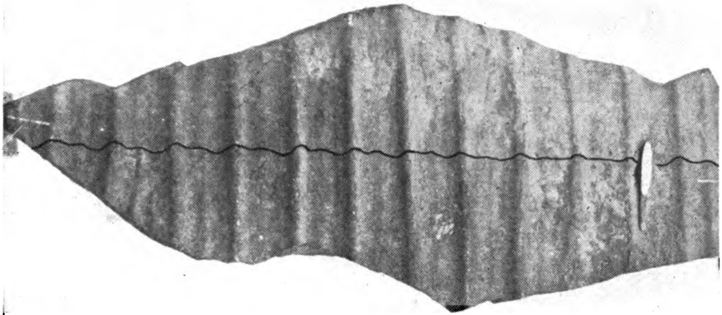

PLATE IV-B.

Unsymmetrical ripple marks with minor crests, which have resulted from combined wave and current action. From Roubidoux sandstone, Rolla, Mo.

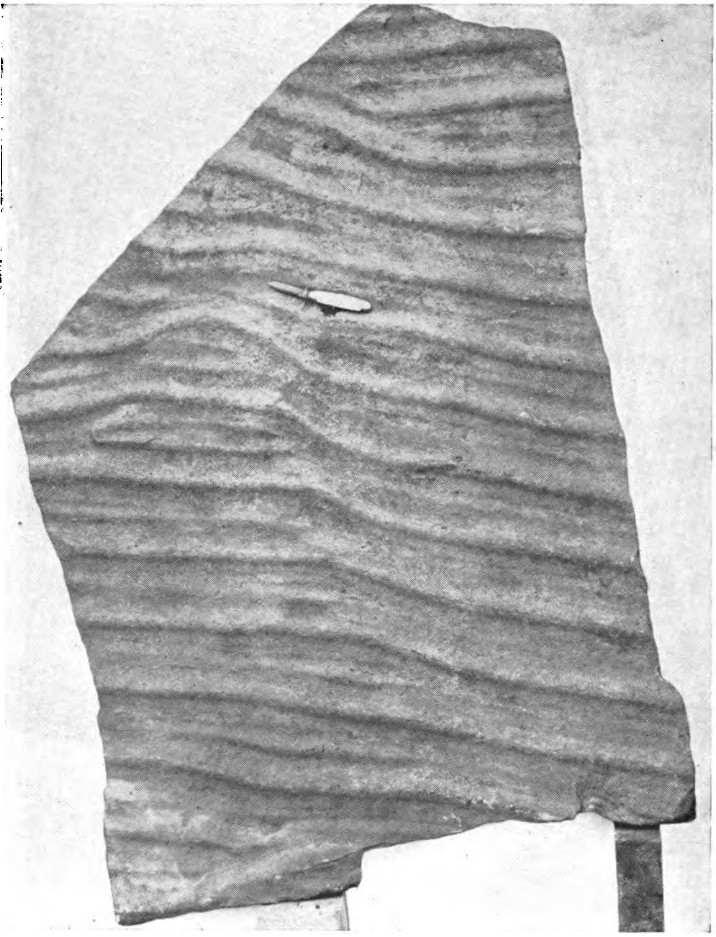

PLATE V.

Mould of wave ripple marks with minor crests. From Roubidoux sandstone, Rolla, Mo.

are much more sharp and narrow than the troughs, and within each trough a small ridge may be developed. (Fig. 3.)

This forward and backward motion of the water particles is in reality an alternating current action, which is the same over all neighboring points on the bottom until acted upon by some irregularity. The resulting ripple marks thus differ in manner of formation from the ordinary current ripple marks (fig. 1) in that here the current moves in alternately opposite directions (fig. 2) for equal periods of time. These ripple marks have, therefore, no lee and stoss sides and are symmetrical, the crests are more narrow and, as seen in cross-section, much more sharply curved than the troughs. The newly created irregularities react upon the moving water and continue its undulatory motion in all directions until it comes within the province of some other center of disturbance or gradually dies out.

The development of the minor crests within the main trough is probably due to the movement of the water in alternately opposite directions. The movement of water in each direction tends to form symmetric ripple marks (fig. 1), the lowest point of the trough of which not being midway between the crests, the effect of the periodic reversals of the motion of the water is equivalent to the superposition of one current ripple mark upon another in a reversed position. The parts which these two have in common is the shape of the ripple that would result in this case (fig. 2), except that the crests would be less pronounced as in figure 3. The longer the wave length and the more nearly symmetrical the character of the ripple mark that would have been formed by the water moving in either of the two directions, the less pronounced is the minor crest. (Pl. VI.) Poorly developed minor crests and a more or less symmetrical character of the major crests often result from true current and wave motions acting together. (Pl. IV-B.) Epry* shows that the ripple marks so commonly found upon the lower beaches are of this type. Kindle** reports that water oscillation resulting from a very gentle on-shore breeze produced in less than three days, under normal conditions in water six inches deep, symmetrical ripple marks with crests distant about an inch and a half and with a slight minor crest in the trough.

---

*Epry, Ch., Smithsonian Institute, Ann. Rept., 1913, pp. 307-318.
**Kindle, E. M., Jour. of Geol., 22, 1914, p. 706.

Wave ripples in Roubidoux sandstone (Ordovician), Rolla, Mo.:

Width.	Depth.	Width-Depth.	Height Minor Crest.
1.2 in.	.13 in.	9.2	.08 in.
1.6 in.	.1 in.	16.	.05 in.
2.2 in.	.15 in.	14.6	.1 in.
3.25 in.	.5 in.	6.5	.5 in.
3.7 in.	.6 in.	6.17	.1 in.

According to Cornish*, "The diameter of the circle and the velocity of the oscillating currents diminish in geometrical progression as the depth increases in arithmetical progression, the diameters being halved for an additional depth of 1/9th wave-length below the mid-level of the surface wave. Thus at a depth equal to one wave length, the diameter of the circle and the velocity of the moving particle of water is 1/512th of that of the surface. Thus, in the case of a wave with a length of 600 feet and a height from trough to crest at the sea's surface of 4 feet, the particles of water at a depth of 600 feet will revolve in a circle of 40+512=0.94 inch diameter. The period of a 600-foot wave is about 11 seconds, and this is the time in which the particle at a depth of 600 feet would describe a circle of about 1 inch diameter."

Grabau** states that according to Siau, the crests of the ripple marks of the haven of St. Giles, on the French Channel, may be distant from 30 to 45 cm. at a depth of 20 meters, while their troughs are from 8 to 10 cm. below their crests. At greater depth their size diminishes. The greatest depth at which they were observed was 188 meters.***

It is seldom that ocean waves obtain so great a length as 600 feet and, while the resulting motion at this depth might be sufficient to produce ripple marks in fine muds, at depth greater than this the agitation caused by the wind-waves must be absolutely insensible and the formation of ripple marks by it impossible.

---

*Cornish, Vaughan, Waves of the sea and other waves, 1910, p. 142.

**Grabau, A. W., Principles of stratiography, 1913, p. 713.

***Hunt, A. R., Proc. Roy. Soc. of London, Vol. XXXIV, 1882, pp. 1-18.

Interpretation.

Jukes and Geikie* many years ago noted the value of ripples in determining top and bottom of beds, and the subject is summed up by Van Hise in his Principles of North American Pre-Cambrian Geology.**

Minor Crests. Van Hise in the above-mentioned paper puts considerable emphasis on the occurrence of small ridges in the troughs between larger ridges. He says: "Normal ripple-marks consist of a series of sharp ridges, separated by rounded hollows, each of which, however, often has a slight sharp ridge in its center. The obverse or casts of such ripple-marks have an entirely different aspect. They consist of broad rounded ridges, each of which has a slight depression in its center, and the ridges are separated by steep depressions. The profile of either of these figures is shown by figure (5), which is placed in a vertical position. One side represents the ripple marks as normally formed, the other their cast or observe. The profile should be turned to the right to bring it back to its original position." (See Pl. IV-A.)

From the frequent observation of such ripple marks with minor crests forming in recent sands, as well as on theoretical grounds, it is safe to say that while minor ridges are found in the major troughs of recent ripple marks, the reverse is true only of casts. This then becomes practically an infallible criterion, where such minor crests are to be found. It must be admitted, however, that both in recent and fossil ripple marks, such minor crests are the exception rather than the rule.

Relative Shape and Width of Crest and Trough. Even though the minor crests may be absent, other ripple-mark criteria are available. On this point also Van Hise says (in the same paper): "The decision may as easily be made even when

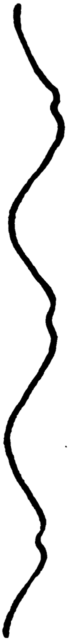

Fig. 5.
Profile of wave ripple mark. (After Van Hise.)

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*Student's manual of geology, 3d ed., 1871. p. 63.
**Sixteenth Ann. Rept., Pt. 1, 1896, p. 720.

the minor elevations in the hollows are absent. In this case, in normal position the depressions are gently rounded, while the elevations are of the same form (sharp ridges) as in the previous case." This statement involves two factors: first, that the crests of recently made ripple marks are sharp, the troughs rounded (Pl. VI); and second, that the crests are narrower than the troughs. (Pl. V.) These factors have repeatedly been used to determine top and bottom of beds.

The unqualified application of this statement to field conditions has been questioned by certain geologists. It is undoubtedly true that many ripple marks, even when newly made, show trough and crest so nearly alike that they are indistinguishable. This is particularly true of eolian ripple marks and of those made by running water, less true of wave-made ripple marks. Of the current ripple mark Grabau* says: "The natural mould (cast?) of this type of ripple will be difficult to distinguish from the natural ripple, though the directions of slopes will be reversed. A careful examination, however, will show that whereas the surfaces of the normal current ripples are gently convex, those of the mould will be gently concave."

It is also true that many ripple marks which when first formed have sharp narrow crests and broad shallow troughs become modified as the waves change amplitude or direction, so that trough and crest are no longer characteristic. But from the study of a very large number of cases, the writers feel confident in saying that ripple marks are never formed and never modified in nature before burial and preservation with relations the reverse of those stated as characteristic. In other words, they have never observed recent ripple marks with crest broad and rounded and with trough sharp and narrow; and forms of such proportions are, with exceptions outlined below, undoubtedly casts, or the imprint of the true ripple mark in the overlying bed.

Mr. Radcliffe** writes as follows: "Vin Hise and others have claimed that the crests of ripple marks are narrower and sharper than the troughs, and one would gather from these statements that not only could the determinations always be made when ripple marks were exposed, but also that the crests of these marks are always more narrow than the troughs. In actual field work in this vicinity, the latter has been found to be true only in about 85 per cent of the cases. Thus, while it is true that in most instances the crests are more narrow than the troughs, it is equally true that in many cases the crests and troughs are of equal width, and that in others the troughs are sharp and narrow, and the crests broad and rounded. It thus becomes evident that care must be used in determining structure by the relative widths of crests and troughs."

---

*Grabau, A. W., Principles of stratigraphy, 1913.

**Radcliffe, D. H., The preservation and interpretation of ripple marks and sun cracks. A thesis submitted to the faculty of the School of Mines and Metallurgy of the University of Missouri in partial fulfillment of the work required for the degree of bachelor of science in general science.

The junior author has examined in detail the ripple marks studied by Mr. Radcliffe. While it is true that many of the troughs and crests are about equally rounded, about equally wide and quite indeterminate, only one case was noted where the ridges were broad and flat and the depressions narrow. (Pl. VIII.) This instance was a group of about fifty adjacent ripple marks which are believed to have been perfectly normal when formed and when buried, but which have had their crests truncated by recent erosion.

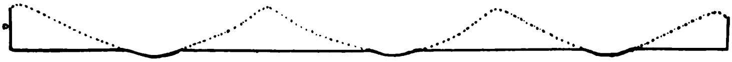

Fig. 6.

Restoration of section of ripple marks shown on Plate VIII. Present profile represented by the continuous line and the original form by the dotted line.

In evidence of this are the facts that these ripple marks lie exposed in a creek bed; that the broad ridges are almost flat and some of them have been nearly effaced; that they are distinctly polished as though by recent erosion; and that the depressions, while narrow, are distinctly rounded, a condition typical of troughs. That such cases are known, even though rare, should compel caution, but the evidence of recent erosion is so plain that they should cause little or no confusion if the observer is on the alert and understands the possibility of their occurrence.

In field application, then, it must be borne in mind that many, perhaps a majority of the ripple marks found preserved in the rocks, are indeterminate, trough and crests so resembling each other as to be indistinguishable. On the

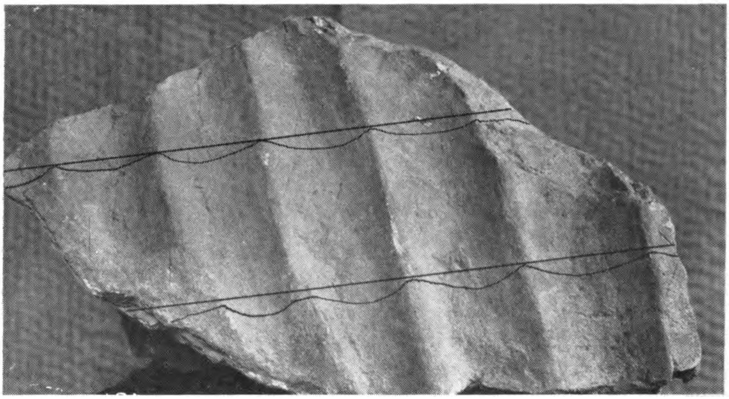

PLATE VI-A.
Mould of symmetrical wave (?) ripple marks. From Roubidoux sandstone, Rolla, Mo.

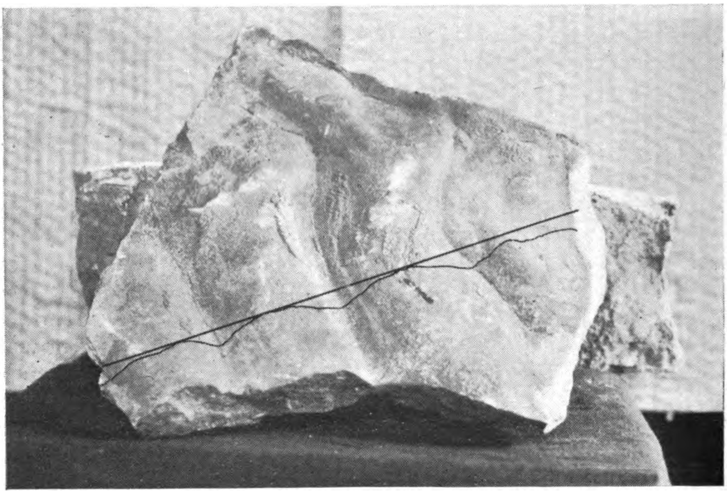

PLATE VI-B.
Cast of symmetrical wave (?) ripple marks. From Roubidoux sandstone, Rolla, Mo.

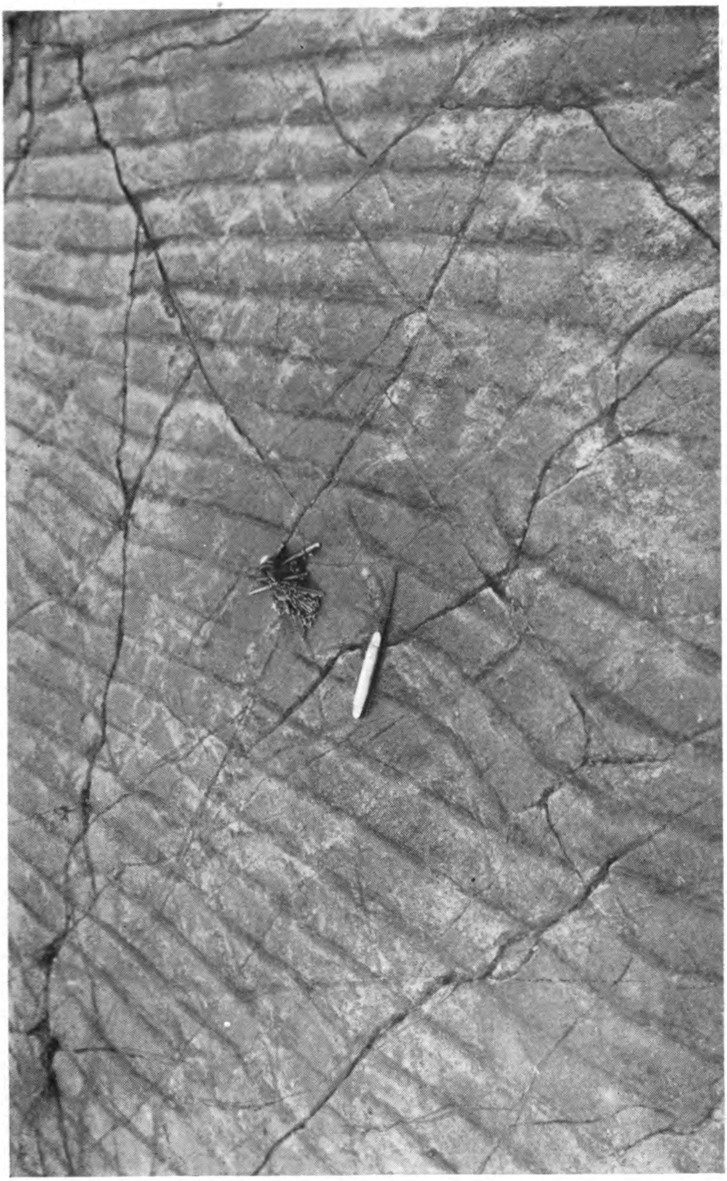

PLATE VII.
Pattern of wave ripple marks shown in Plate VIII.

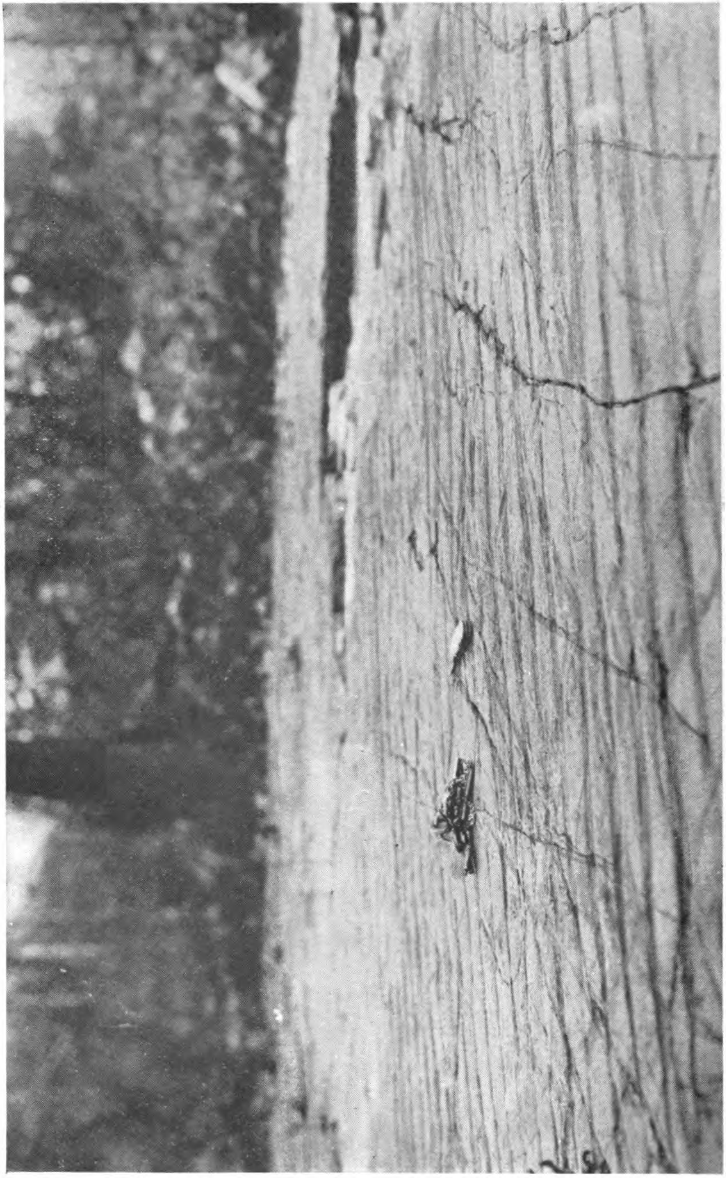

PLATE VIII.

Deceptive wave ripple marks which have resulted from a partial erosion of normal ripple marks. Roubidoux sandstone, Rolla, Mo.

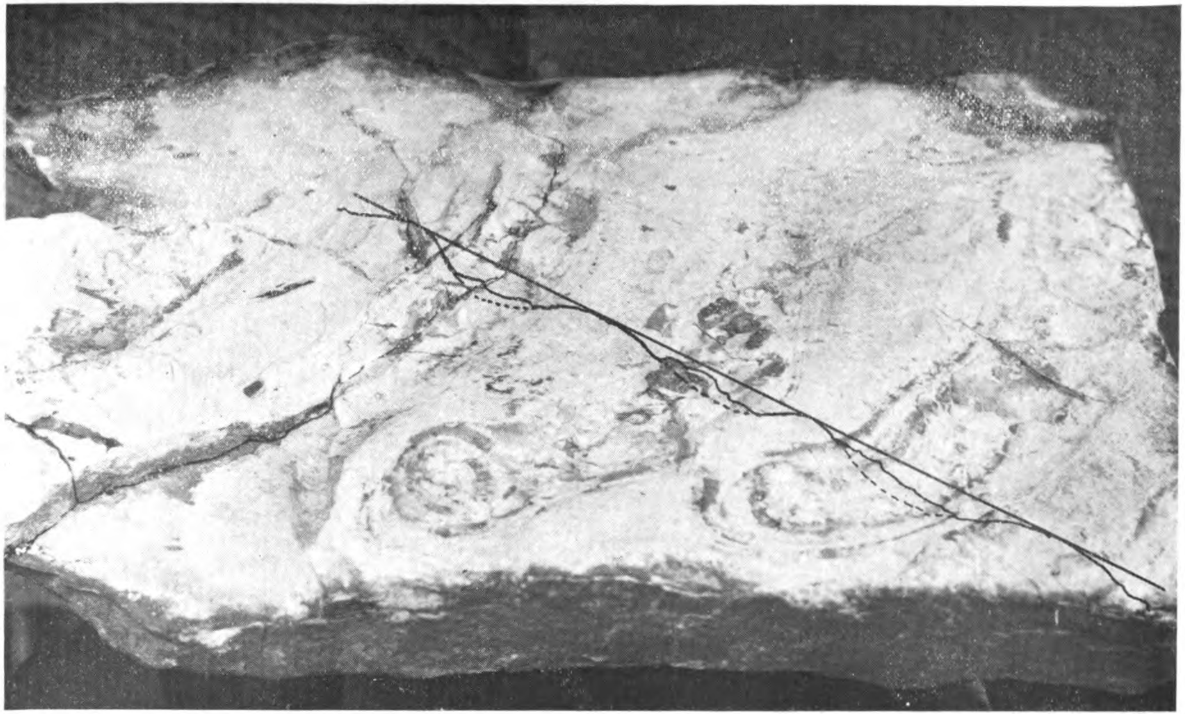

PLATE IX.

Mould of current ripple marks with "filled troughs," from sandstone layer in Jefferson City formation. Rolla, Mo.

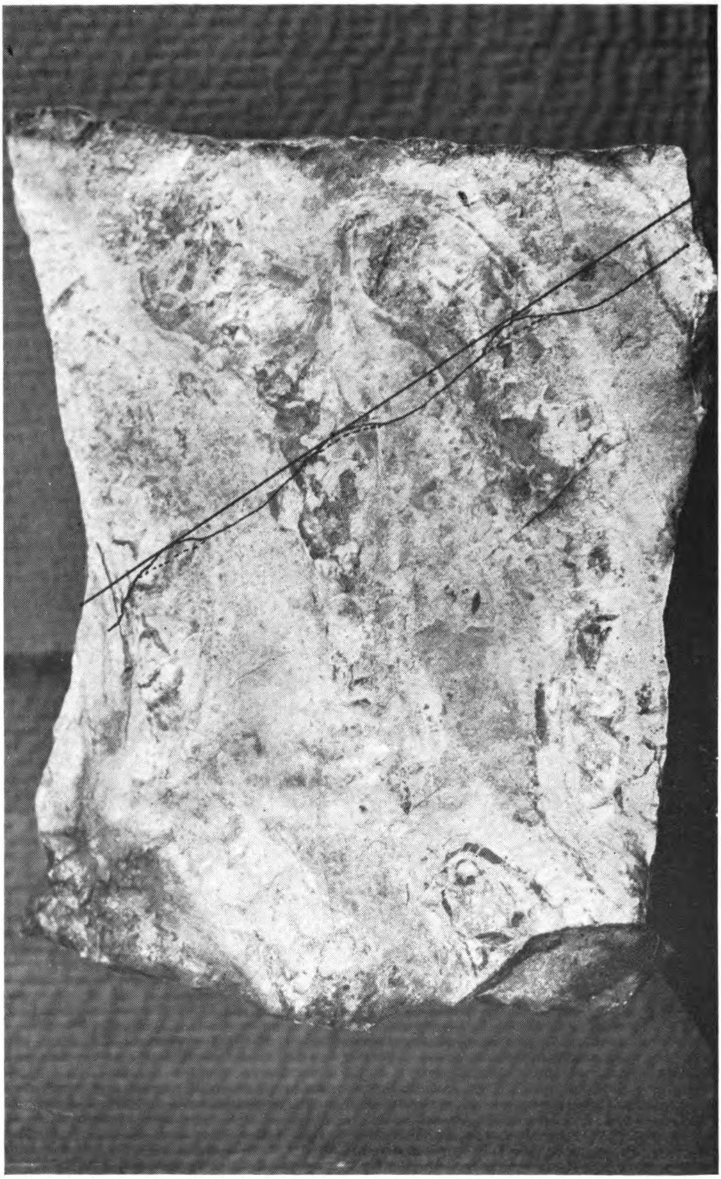

PLATE X.

Cast of current ripple mark shown in Plate IX. Profiles shown coincide when two pieces are placed together.

other hand, where trough is broad and gently rounded and crest notably sharper, there can be but little doubt that we are dealing with the mould or true ripple mark; while when the ridge is broad and gently rounded and the depression sharp and narrow, the form is undoubtedly a cast, representing the base of the overlying (younger) bed.

Filled Troughs. The senior author and Mr. Radcliffe* in a study of local ripple-marked beds noted that many of the troughs were partially filled by discontinuous layers of material which lie upon the wave surface (Pls. IX and X), the significance of which Mr. Radcliffe sums up as follows: "This material will naturally be deposited in the troughs, with perhaps the exception of a very thin film on the crests. Upon deposition of the next stratum this foreign material will be kept firmly in place so that the troughs of the ripple marks will contain most of the foreign material present, while the crests will be tight against the adjacent layer. The converse will be true of the casts." Observation of a considerable number of these filled ripple marks in place in beds known not to be disturbed shows that the filling material accumulated in the troughs. For practical purposes, then, when such material fills the depression, it may safely be assumed to be the trough of a true ripple mark (Pl. IX); while if more rarely it is found capping a ridge (Pl. X), the ridge may be assumed to be the cast which formerly filled the trough.

Texture. A possible explanation of some cases of what appears to be a filling of a trough is that it merely represents the sorted coarser material of the sand which, due to its greater weight, accumulated in the trough. This is more likely to be true of subaqueous than of superaqueous or wind formed ripple marks. "In the distribution of the material in the wind ripples, there appears also to be a distinctive character, in that the coarser material is found on the crest of the ripple, instead of in the trough as in subaqueous ripples."** In making any application of this change in texture it may be necessary to determine whether one is dealing with subaqueous or wind made ripple marks, a condition which renders the value of the criterion problematical, unless the banding of the filling shows clearly, as is the case in Plates IX and X, that it was deposited in a depression.

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*Thesis, Op. cit.

**Grabau, A. W., Op. cit.

Summary. Minor crests, though by no means as common as is implied in published accounts, give the best evidence of structure where observable. Marked disparity in width and sharpness of trough and crest is almost positive evidence. As the trough and crest become less and less pronounced, cases become less definite until they may be wholly indeterminate, a condition obtaining in a large number of observed ripple marks. Filled troughs may offer strong confirmatory evidence. In rare cases truncated ripples may occur, but the peculiarities of extremely flat ridges, polished by recent abrasion, should make it possible to detect their origin and prevent structural misinterpretation.

CROSS BEDDING.

Cross bedding is preserved depositional bands at an angle to the true bedding in sediments, and is the result of current action. It can therefore be formed at any depth and in any kind of mechanical sediments, but is formed most abundantly under eolian and shallow water conditions and is most commonly preserved in sandstones. For a number of years it has been used in determining the top and bottom of beds that have been folded. About 1910 Professor Smythe in a conversation mentioned the fact that Professor Davis had used this criterion for many years with classes in the field. This is the earliest account of its use the writers have been able to find. Leith* includes it in his text-book on structural geology.

Cross bedding may be produced by wind action in dune sands and by water currents where detrital material is being deposited or reworked, as along shore lines in beaches, spits, and similar forms, and in river bars. Thus grains of sand are carried along by currents of air or water until they encounter a depression into which they roll, forming successive inclined layers over the inclined surface. As a rule the dip and curvature of the inclined layers become less marked the further they are traced down the dip from the crest, until the false bedding formed thereby approaches the horizontal. Usually the layers tend to meet the overlying true bedding plane at a large angle in marine deposition where the bottom and the currents are more or less uniform and regular. This condition is often accentuated by a slight

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*Leith, C. K., Structural geology, 1915, p. 132.

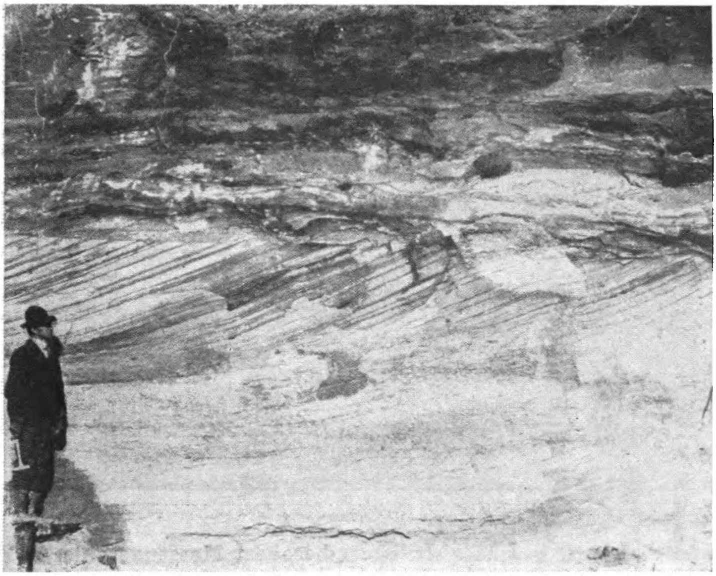

PLATE XI-A.
Cross bedding in Tuscaloosa sands near Iuka, Miss. (U. S. Geol. Survey.)

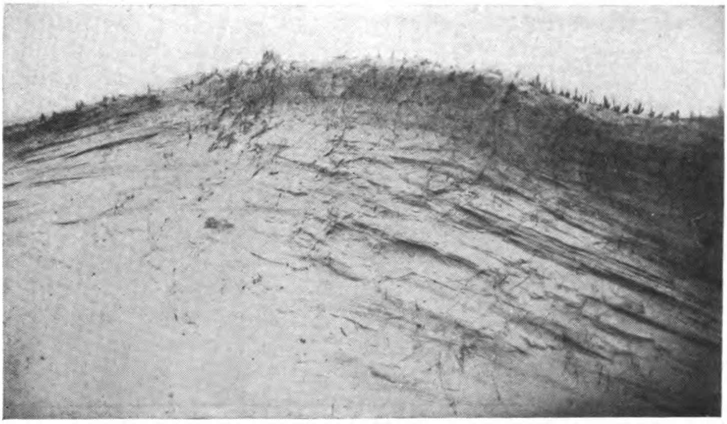

PLATE XI-B.
Irregular bedding in dune sand.

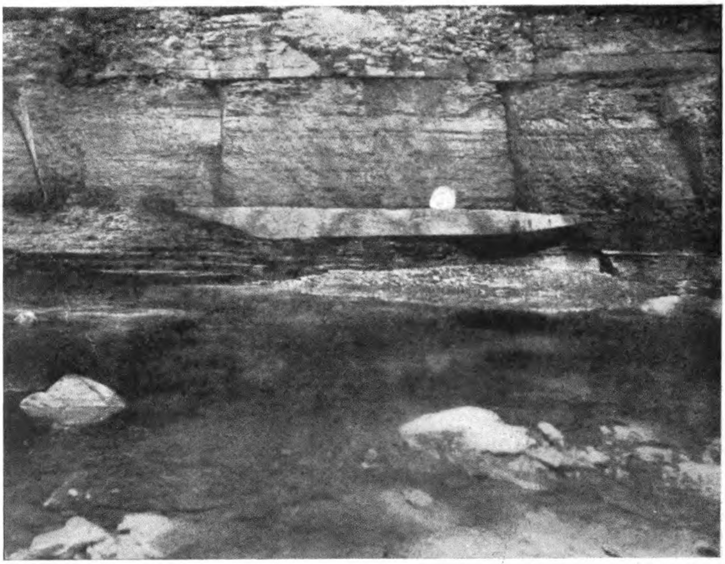

PLATE XII-A.
Sandstone lense in Ithaca shale member, near Messengerville, N. Y.
(U. S. Geol. Survey.)

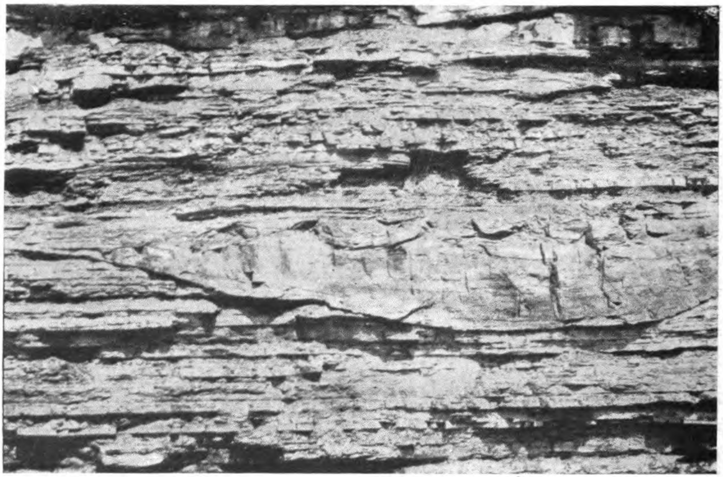

PLATE XII-B.
Marine unconformity in Medina formation, Niagara gorge, N. Y.
(U. S. Geol. Survey.)

erosion of the top of the containing layer. (Pl. XI-A.) Where the surface is uneven and the currents irregular, as under eolian conditions and in streams, it is not uncommon to find the top as well as the bottom of the banding grading into the horizontal. (Pl. XI-B.) In such cases both ends of the false bedding approach tangency to the true overlying and underlying beds and tend to obscure any structural interpretation. (Fig. 7.)

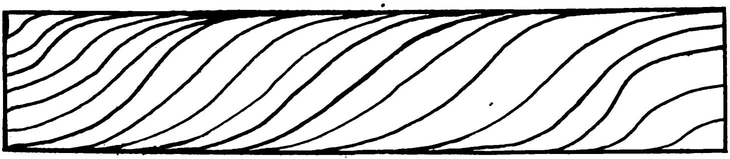

Fig. 7.

Section of cross bedding approaching parallelism to the beds both above and below.

The formation shown in Plate XI-A is undoubtedly right-side up, because the marked concavity of the banding is upward and the large angle at which inclined beds meet the true bedding plane is on the upper side. Cross bedding as developed in limestone generally has a lower angle of dip and shows less curvature than in sandstone, and is often indeterminate because it cannot be traced to its points of contact with the true overlying and underlying bedding planes. The many observations of cross bedding in undisturbed beds made by the writers, both where developed on a large scale in sandstones and on a minute scale in shales, seem to warrant the statements that, while some occurrences of cross bedding are indefinite, in no case should a careful study of cross bedding lead to a misinterpretation of structure, and that under no conditions will the angle made by the banding and the bed below be greater than that made by it and the overlying stratum. If this be true, all cases where the inclined layer approaches tangency at one end and makes a large angle at the other should be capable of positive determination. The less marked the curvature of the banding and the less pronounced the difference between these two angles, the more uncertain is the conclusion; and, as in all problems of this sort, the greater must be the number of confirmatory tests. A single well marked case should be conclusive.

Due to its widespread occurrence cross bedding is probably of more actual value in determining the top and bottom of beds than any other structure.

LENSES OF MECHANICAL DEPOSITION.

Lenses are characteristic of shallow water conditions, where currents vary in intensity and where detrital material is being deposited and reworked. Under such conditions, local currents may for a time either prevent the deposition of material at some point or actually scour out some of the loose, unconsolidated sediment, forming a trough-shaped depression or pit. Such irregularities may become more or less filled with detrital material which differs from that below and above either in texture or kind (usually more coarse and sandy), because of the increased carrying power of the water due to its locally greater velocity. A cessation or removal of the exceptional conditions permits the renewal of normal deposition and results in the inclusion of this material as a lense in the former depression.

It will be found that such lenses tend to be plano-convex in shape, the side with the less curvature being the top. (Pl. XII-A.) Naturally such lenses will vary in size and in the degree of readiness with which they can be interpreted. As the size increases, both the relative and the absolute curvature of the bottom decreases. Probably the best size for field interpretation is one having a maximum width of between four and ten feet.

MARINE SCOURS OR UNCONFORMITIES.

As outlined above, it is recognized that here and there in the sea, currents exist which may not only prevent deposition along their course, but which may even scour out the unconsolidated material below, producing troughs in what is otherwise a rather uniform plane of deposition. With the removal of these conditions and the renewal of normal sedimentation, such breaks in the continuity of deposition may be recognized by differences in bedding, texture, or material. This is similar to the formation of lenses, but differs in that it is a larger and more continuous structure, and in that the filling itself may show well marked bedding and does not differ lithologically from the overlying stratum. If the erosive action has been quite extensive, the tops of the ridges formed will tend to lie in the same plane as do the tops of ridges which mark a former peneplane, while the depths of the troughs formed will be quite variable. In any case, however, the bedding of the younger strata will tend to parallel the contact while that of the older will often terminate abruptly against it. (Pl. XII-B.)

UNCONFORMITY.

A land unconformity may be used in the same manner as described above. Where there has been considerable erosion or where there is a marked discordance in bedding, it will be easy to see that the bedding of the younger formation will tend to parallel the contact, while those of the older formation will be truncated by the plain of the unconformity and by the erosion channels. Inasmuch as unconformities are commonly overlaid by conglomerates and sandstone, it follows that if one side of the unconformity was marked by such a rock, it is quite probable it represents the younger formation. It is also true that the younger bed often contains fragments of the older which can be clearly recognized as such. Differences in metamorphism, instrusion, etc., would also tend to mark the older formation.

RILL MARKS.

During the retreat of the water on tidal flats, small branching channels resembling minute drainage networks are frequently cut in the mud. Where streamlets branch into distributaries on small fans, cones, or plain surfaces, somewhat similar systems of channels may be found. They may often be noted on mud flats after a shower. These sediments may become buried beneath later layers of sand or clay

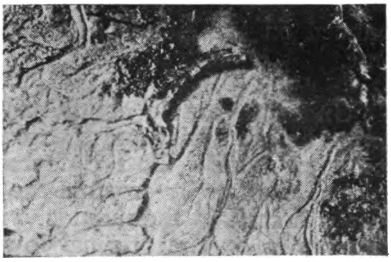

Fig. 8.
Rill marks resembling impressions of sea weeds. Beach of Noyes Point. R. I. (Walcott, U. S. Geol. Survey.)

with the complete preservation of the rill mark. If exposed by subsequent erosion, the mould or original rill marks will be concave (fig. 8), while the cast will show in relief on the true bottom of the younger bed.

These structures are not often sufficiently well preserved to serve as indicators of structural attitude, but are worthy of a careful search when the other criteria present are indecisive.

RAIN PRINTS.

Brief showers of rain or hail, especially when only a very few drops or pieces fall, often leave their imprints on soft clay surfaces. These are known as rain prints and consist of shallow circular depressions, not infrequently surrounded by low rims of the mud forced out of the depressions. (Fig. 9.) If the drops are driven by a hard wind, the rims are usually more pronounced on the side opposite that from which the drops come.

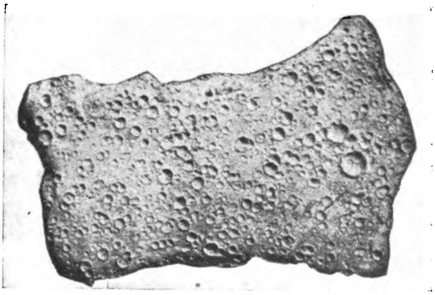

Fig. 9.
Rain-drop impressions. (Brigham).

Under favorable conditions the imprinted mud may harden before burial and the structure be preserved by the next layer which fills the depressions or "prints." When exposed later, as by erosion, the surface of the rain-printed layer will contain the moulds, while the casts will show as the pimples on the original lower surface of the younger bed. Figure 9 shows the moulds and represents the top of the older bed. These phenomena, while not abundant, are by no means rare and, when well preserved, may serve to determine the structural attitude of the beds.

ANIMAL TRACKS.

It is not unusual to find in terrestrial deposits well preserved foot prints of animals. The animal walking over a muddy surfare leaves a well marked line of foot prints, which may be perfectly preserved if the mud dries sufficiently quick, and the surface is then covered with another layer of sediment, which fills the depressions. Upon future exposure the older layer will contain the mould and the younger bed the cast. Figure 10 shows the photograph of a mould, or surface of the older bed. Figure 11 shows an artificial cast and illustrates the normal apearance of the original under surface of the younger bed.

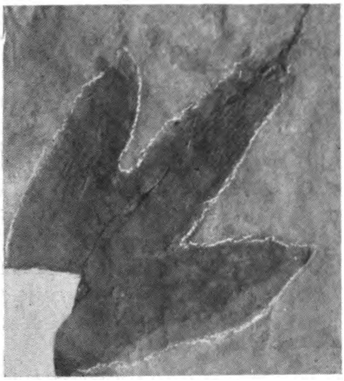

Fig. 10.
Mould of animal foot print.

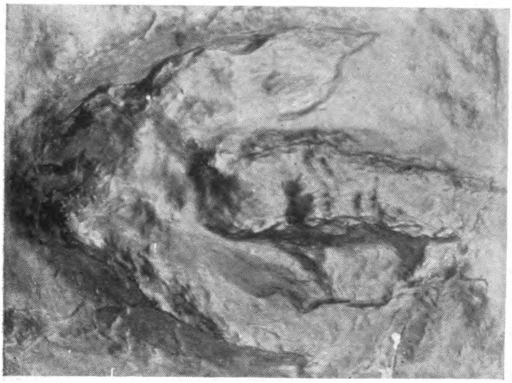

Fig. 11.
Cast of animal foot print.

Where sufficiently well preserved, animal prints may give a clue to the structural attitude of the strata.

FOSSILS.

Structures.

The records left by marine organisms have usually been so thoroughly broken and scattered as to be illegible in structural terms except as outlined later under fossil succession. There are, however, certain structures, such as the traces of cavities left by boring mollusks and the outlines of cryptozoons, corals, etc., which may, when preserved, be used with positive results.

Mollusks.—Lawson has for years used the traces of the cavities made by boring mullusks to determine the structural positions of certain Tertiary formations. Such animals bore holes on a wave-cut rock surface which increase in diameter downward.* (Fig. 12.) The preservation of such bores by fillings different from fillings of cavities produced by boring mullusks. The containing rocks offers absolute evidence as to the side of the unconformity on which the older formations lie, the direction of the base of the hole being determined either by a variation in size or by the rounded end of the filling. (Fig. 13.)

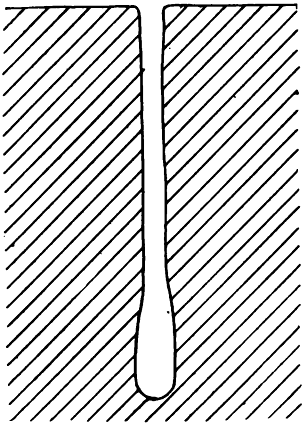

Fig. 12.
Fillings of cavities produced by boring mollusks.

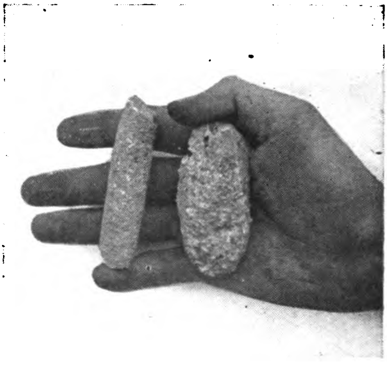

Fig. 13.
Section of cavity produced by boring mollusks.

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*Lawson, A. C., Dean of the School of Mines, Univ. of Cal. Personal communication.

Cryptozoons.—In 1913 Barrell*, by the use of cryptozoons in the Cambrian-Ordovician limestones of eastern Pennsylvania, was able to work out an overturned section of limestone which was not evident by any other means. While cryptozoons differ considerably in shape and size, their upper surfaces and septæ are markedly convex upwards. (Pl. XIII.)

Corals, etc.—In view of the use of cryptozoons, mentioned above, there is no apparent reason why fixed corals, stumps in situ in coal beds, and possibly other organisms, may not be used in determining structure.

Succession.

During the passage of geologic periods all branches of animal life experienced development changes, many of which are preserved by fossil forms. Such changes, in the course of time, were of slow development so that for a difference to be recognized it is necessary for the two containing beds or formations to differ in age by thousands of years and, unless the continuity of deposition was broken, usually by a considerable thickness of sediments. However, this fact is of but slight importance; for even when it is not possible in the section exposed to determine the relative ages of the beds by the amount of evolution exhibited, it is frequently possible to determine which is the younger and which the older bed by a comparison with the known fossil succession from some undisturbed area not too far distant. In fact, this is the usual way, in actual practice, that fossils are used in working out structure in folded regions. The method is particularly applicable in areas where the formations are thin, and where the contained fossil forms have a very restricted vertical range, in extreme cases, only a few feet.

This method is closely related to that outlined in the following section.

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*Barrell, Joseph, Professor of Geology, Yale University. Personal communication.

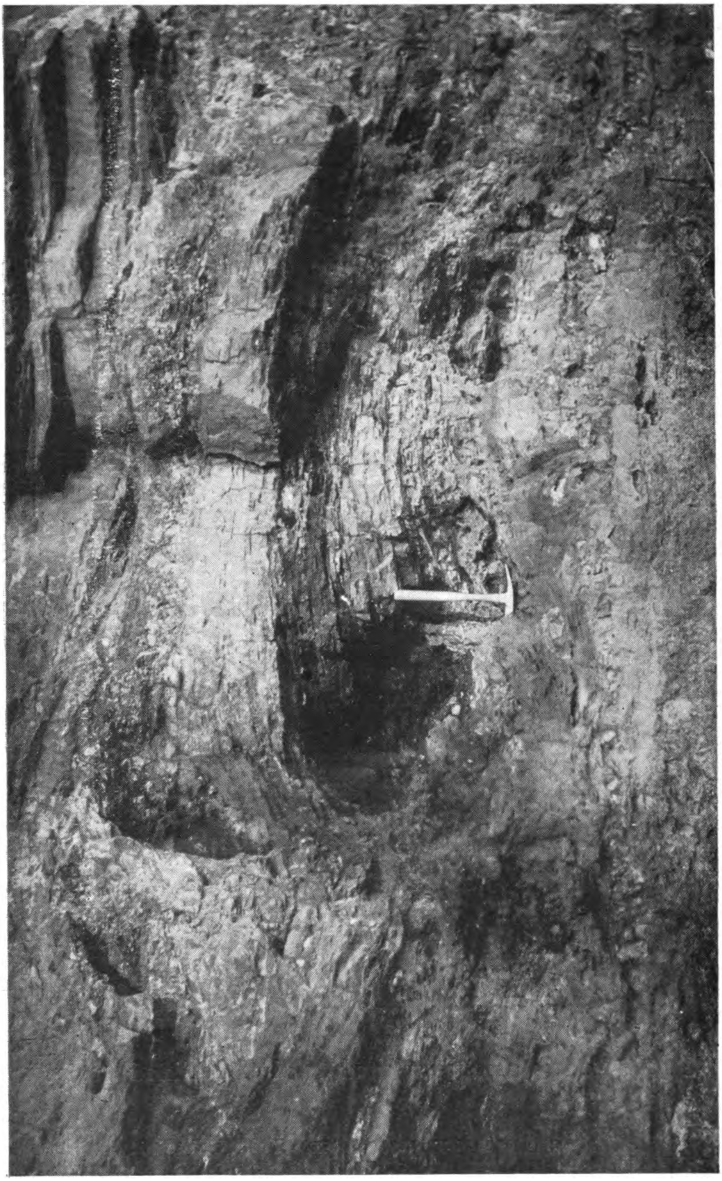

PLATE XIII.
Large cryptozoons near top of Gasconade dolomite near Rolla, Mo.
(Missouri Bureau of Geology and Mines.)

COMPARISON OF SEQUENCE.

When the true sequences of the beds or formations to be considered are known or can be determined elsewhere in terms other than their fossil contents, such as lithological character, texture, thickness, color, bedding, etc., the structural position of any bed can be readily determined by comparison of its sequence with that of the known area. If the beds are found in the reverse order from that which they are known normally to occupy, it is evident that the formations have been overturned. The chief caution to be observed in using this criterion is that which applies in all correlation by lithologic evidence, namely, that formations widely separated in time may closely resemble each other. If, however, the correlation is sound, the structural interpretation of top and bottom must also be sound.

MUD CRACKS.

Wherever extensive mud flats are exposed sufficiently long to the drying effect of sun and air, the loss of water results in a shrinkage. Tension cracks, known as mud cracks, or sun cracks (also described as dessication figures), are formed which cut up the mud surface into polygonal blocks. (Pl. XV.) The more rapid drying of the mud near the surface causes the greatest shrinkage at the top so that the cracks are wedge-shaped, varying from a fraction of an inch to several inches across at the top, and tapering down to actual disappearance at depths limited only by the amount of dessication in those cases in which the mud layer is of sufficient thickness not to be cracked entirely through. The depth of such cracks varies from a few inches to ten or fifteen or even more feet. It is a very common phenomenon for the mud layers adjacent to mud cracks to curl up (Pls. XIV and XV) and, under very favorable conditions, for the outlines of the curved laminæ to be preserved along with the filled cracks.

There seems to be some dispute as to the method of preservation of mud cracks. It is agreed, however, that the cracks and the spaces underneath the curled laminæ may become filled with other material, usually sand, so that upon consolidation the outlines of the cracks and the fillings are preserved. In some cases this may result from submergence, but probably more often it is the result of eolian action.

So far as the structural interpretation is concerned it is immaterial how the cracks became filled.

Field work by both authors shows two rather distinct types of mud cracks; one extending to any depth, the thickness of the mud layer being so great that the crack does not extend to the bottom; and the other being limited in depth by the thickness of the mud layer, which is cracked entirely through. The former type is the one usually described; nothing concerning the latter type appears to have been published.

Unlimited Mud Cracks.

Mud cracks, the depth of which has been limited not by the thickness of the mud layer, but only by the amount of dessication, are characterized chiefly by a wedge-like section and irregular depth, and differ thereby from the limited type. (Compare figs. 14 and 15.) They are found preserved in many rocks and are described in all text books on general geology.

Limited Mud Cracks.

During several years of teaching and field work in the Ozarks at the Missouri School of Mines and Metallurgy, the writers have had opportunity to study a large number of mud cracks which seem to be of a type somewhat different from those outlined above. These cracks are figured in the report on the Rolla Quadrangle*, but no attempt is there made to explain their peculiarities. D. H. Radcliffe**, in an unpublished paper, says of them: "The formation of sun cracks in this (the usual) manner is undeniable, but field evidence does not show that they are all formed in precisely this manner, for there is evidence of well marked sun cracks which do not extend down into the rock upon whose surface their weathered forms occur, but seem to be cemented to this surface.

"The materials composing both the rock and the ridges are the same, being a sandstone, so well cemented as to approach the quartzite condition. There is no perceptible break in the bedding of the sandstone immediately below the

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*Lee, Wallace, Missouri Bureau of Geology and Mines, Vol. XII, 2nd ser., Pl. VIII, 2.

**Op. cit.

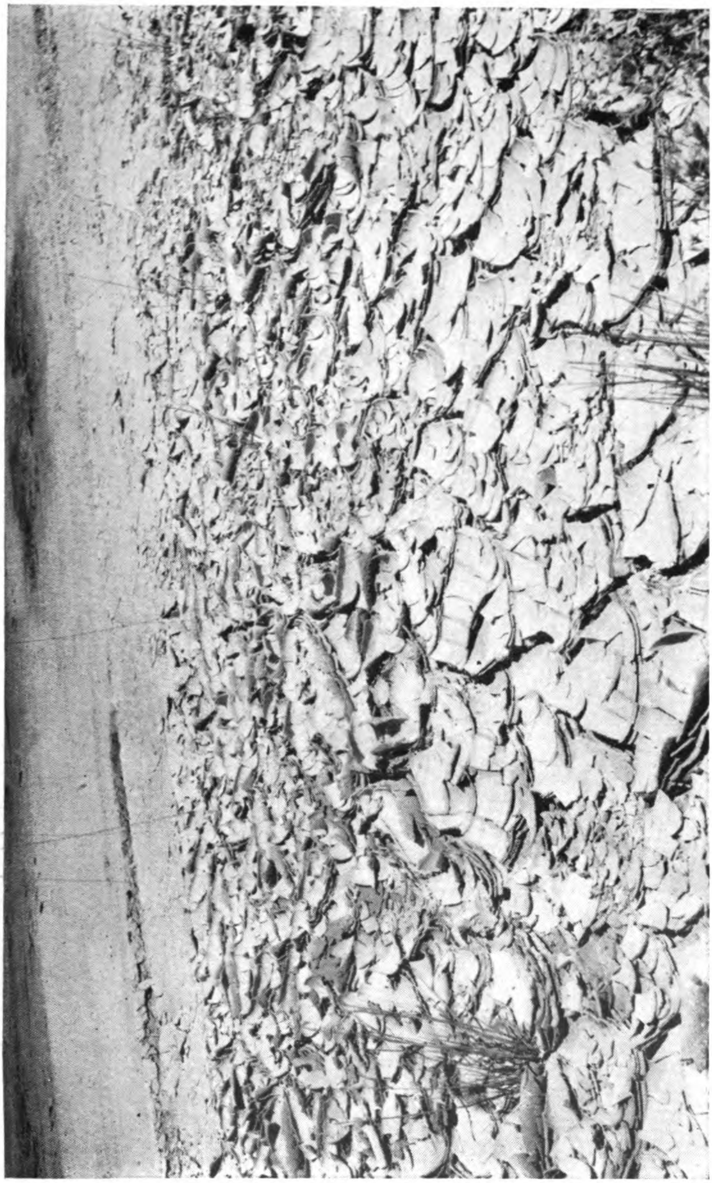

PLATE XIV.
Mud cracks with curled laminae near Maricopa, Cal.

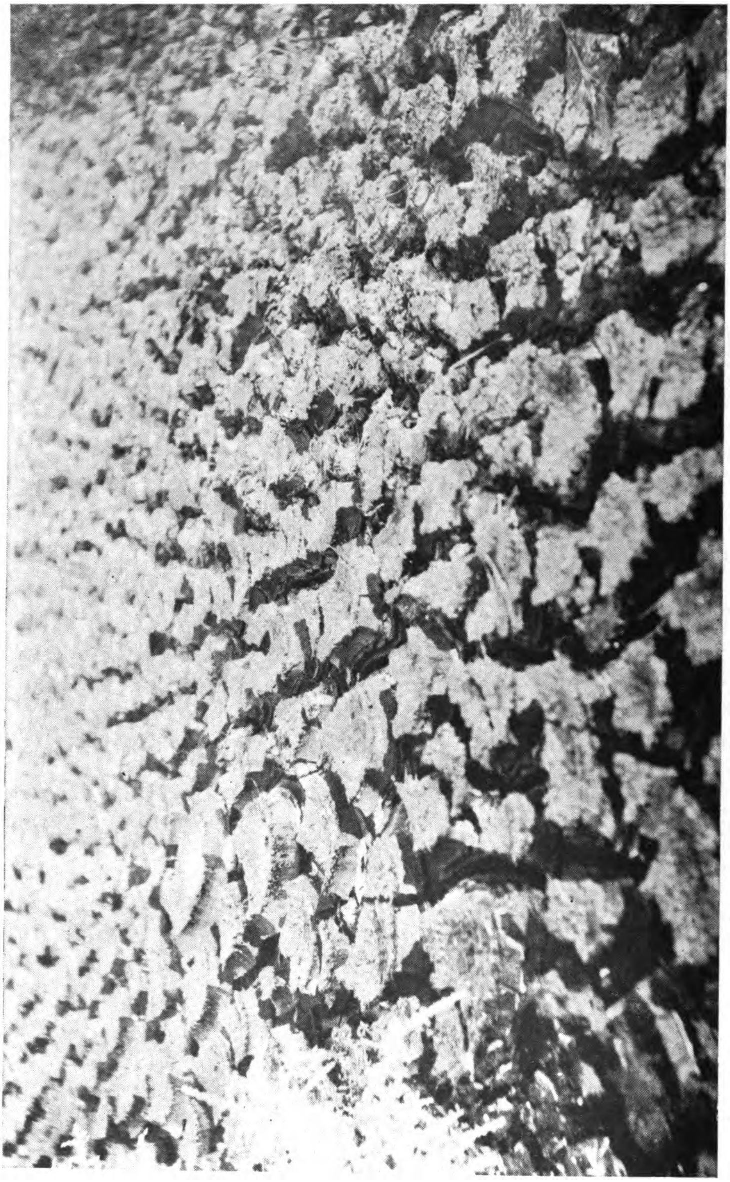

PLATE XV.
Sun cracks in asphaltum near Taft, Cal.

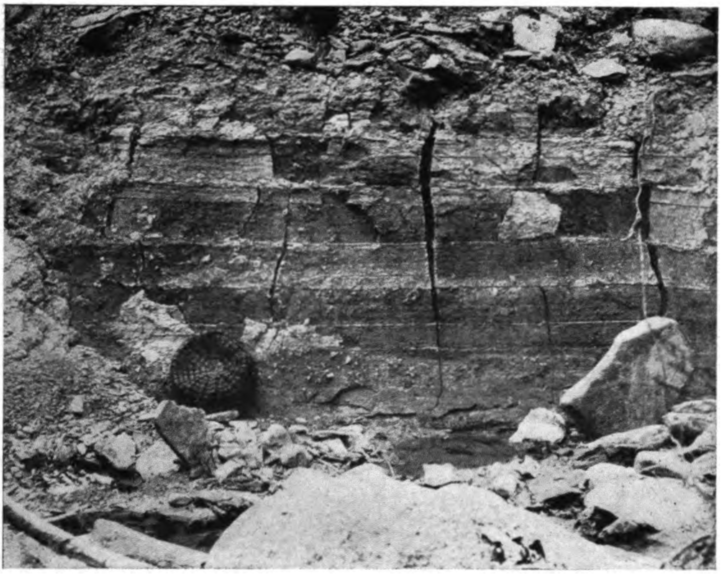

PLATE XVI-A.
Dessication cracks in glacial clay showing wedge-shape and irregular depth. (U. S. Geol. Survey.)

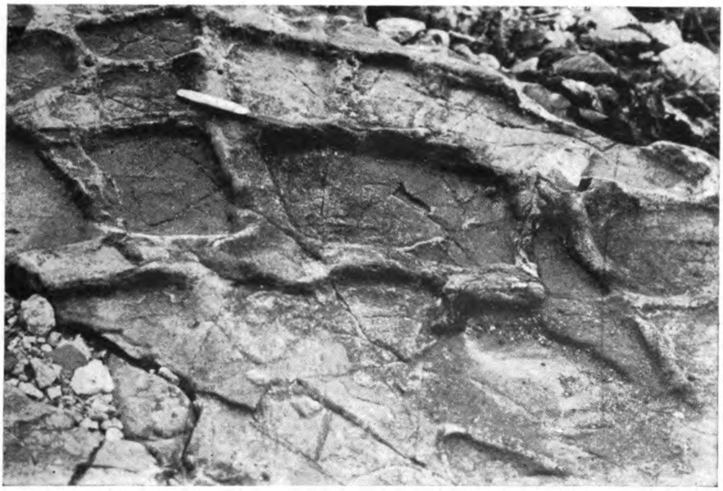

PLATE XVI-B.
Limited sun crack fillings adhering to lower (older) bed. Roubidoux sandstone, Rolla, Mo.

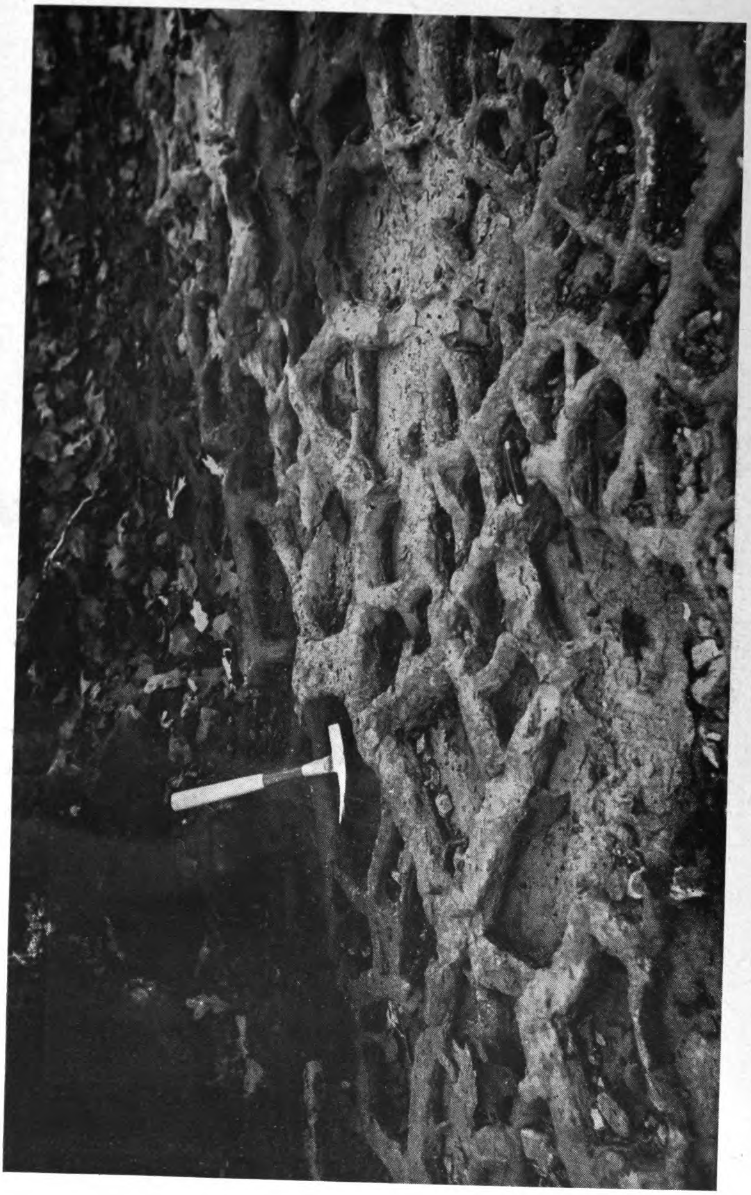

PLATE XVII.

Limited sun crack fillings adhering to lower (older) bed Roubidaux standstone, Rolla, Mo. Missouri Bureau of Geology and Mines.)

ridges, and the ridges terminate abruptly against the underlying rock. Such sun cracks were probably formed under conditions where a layer of mud, or other soft material, was deposited upon the surface of a sand layer. Upon exposure the mud, because of its high shrinkage, was cracked through, while the sand, having no shrinkage, was unaffected. The shape of the cracks formed in the above manner will depend upon the thickness of the layer of mud. Thus if the mud is thick the shrinkage diminishes with depth and so produces a wedge-shaped crack; but if the mud layer is thin, the whole shrinks, producing cracks wide at the bottom. Upon or before resubmergence, sand is deposited in and over the cracks and mud. Then upon partial cementation of the sand, the result is two distinct layers of sandstone separated by a layer of mud, and in the case of the thin mud bed, joined to each other by the crack-filling material. Upon the erosion of the upper layer of sandstone, the mud which had separated the two layers would be washed away, causing the crack-filling material to stand out in bold relief and fulfill the conditions as they have been found." (Pls. I, XVI-B and XVII.)

To the statement made by Mr. Radcliffe, it may be added that the ridges noted have in many places been found in situ, projecting upward from the surface of the outcrop of undisturbed beds, so that there can be no possibility whatever that they represent the case shown in figure 17a, where the filling has adhered to the underside of the overlying bed.

For some time evidence has been sought to corroborate Mr. Radcliffe's explanation, and several cases have been noted where a thin layer of mud has been cracked completely through, exposing the underlying layer of sand. No case of the recent filling of such cracks has been observed, but it is evident at a glance that a layer of sand sifted over the cracked and dried mud would give conditions identical with those postulated in the above quotation.

Interpretation.

It has been recognized for a number of years that mud cracks could sometimes be used in distinguishing between top and bottom of beds; and that they might therefore be used in determining whether or not the containing strata has been overturned. Barrel, in a recent personal letter to the junior author, states that, "Mud cracks buried by eolian sands are characterized by dish-shaped surfaces concave upward. This feature, of course, as well as the fact that the filling extends from the bed above would serve to show which was the upper side of an overturned stratum. The feature of concavity was first pointed out in the paper on the Origin and Significance of the Mauch Chunk Shale, Bull. Geol. Soc. America, Vol. XVIII, 1907.—I have never published any paper pointing out the use of sedimentary structures for determining the structural attitude of the bed, although I have used them in my lectures in structural geology."

Thwaites* refers to their possible use in working out the structure of the overturned Lake Superior sandstone, but states that for the most part the preservation of the structures in these formations is so imperfect as to preclude their use.

So far as the authors have been able to discover, no critical estimate of the value of mud cracks in determining the strutctural attitude of beds has ever been published.

Filling often adheres to overlying bed. If the filling, which is often of more resistant material than the cracked shale, should alone be preserved adhering to the younger bed, the appearance might be as in figure 14. In this case it is clear that the narrow points of the crack fillings show the direction of the base of the containing bed. This is the case cited by Barrell in the above quotation where he says, "The filling extends from the bed above," and mentioned by Gilbert**, "Where the under surface of the Vermilion sandstone is seen to be marked by a network of ridges which once occupied the sun-cracks of the Shinarump clay." (Fig. 14.)

Walther*** calls attention to the same phenomenon in the following paragraph: "Feuchter Tonboden, wie er, in den grossen Takyrflächen von Transkaspien ausgedehnte gebiete gedeckt, reisst bald nach dem Ende der Frühjahrsregen durch tiefe Trockenrisse in polygonale Felder, die 5-50 cm. Durchmesser haben und bis in den Herbst konserviert werden. Am Tempel von Abu Simbel in Nubien, wo der gelbe libysche Sand über eine Felsenwand nach dem Nilufer herabgleitet, war der schwarze Nilschlamm durch Trockenrisse in 40 cm. breite Felder geteilt, wie grosse Basaltsaülen von metertiefen Klüften umgrenzt. Der gelbe Dünensand rinnt in diese Trockenrisse hinab, und verdeutlicht, wie über einer eingetrockeneten Tonfläche eine Sandsteinbank entstehen kann, deren Unterseite mit Netzleisten bedeckt ist."

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*Thwaites, F. T., Sandstones of the Wisconsin coast of Lake Superior; Bull. Wis. Geol. & Nat. His. Survey, No. XXV, 1912, p. 53.

**Gilbert, G. K., Geology of the Henry Mountains, U. S. Geog. and Geol. Survey, Rocky Mtn. Region, 1880, p. 9.

***Walther, Johannes, Das Gesetz der Wuestenbildung in Gegenwart und Vorzeit. Leipzig, 1912.

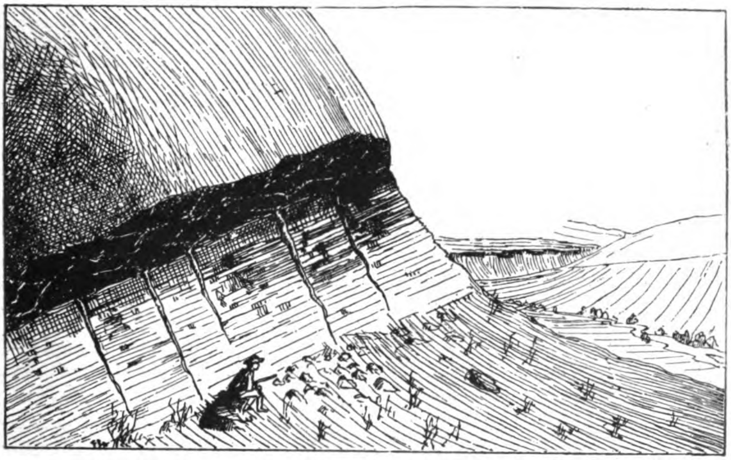

Fig. 14.
Preserved mud cracks. (After Gilbert.)

Geikie* also emphasizes the same point. He says, "The casts usually adhere to the overlying stratum, of which, indeed, they form a part."

It is evident from the above quotations that heretofore it has been assumed that the filling of the cracks adheres to the younger rock only. The recognition of the limited type of mud crack shows that care must be used in interpreting this data; and the very frequent occurrence in the Ozark region, especially in the Roubidoux sandstone, of such ridges projecting upward from an undisturbed sandstone makes it evident that this may be a source of error in determining the top and bottom of beds, unless the observer is constantly on guard. It has been suggested that in any case the layer would adhere more strongly to the younger bed, but this is not apparent in the very many cases examined. Whatever the position of the beds, and which ever layer is removed by erosion, the mud crack fillings are found adhering to the unremoved layer. Limited cracks are therefore indeterminate by this method.

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*Geikie, James. Structural and field geology. 3d ed. Revised, 1912.

Mud crack fillings, the depth of which has not been limited by the thickness of the mud layer, will almost invariably adhere strongly to the upper layer and partake of its nature. Thus when one knows that he is dealing with the unlimited type, the determination can usually be readily made. In figure 15 the beds are obviously in the normal position. The value of this criterion is much decreased by the fact that in determining whether one is dealing with the limited or the unlimited type, he will often use evidence, such as "wedge-shape" and "irregular depth," which can just as well be used directly for the structural determination.

Curled laminæ.—Since the loss of water and consequent shrinkage are greatest near the surface, there is a marked tendency for the mud to curl up in thin laminæ. In studying recently formed mud cracks on the mud flats along the Mississippi River and in Southern California, numerous cases were noted where successive laminæ showed distinct curvature, the upper layer curling the most and splitting away from the one underneath, which in turn showed less curling and was split away from the following layer. (Pl. XIV.) The thickness and curvature of such laminæ seem to depend chiefly upon the bedding within the original material and the rate of dessication.

The preservation of the shapes of the upper and lower surfaces of the laminæ and the horizontal openings between them may be of considerable assistance in determining the top and bottom of beds. This is the condition mentioned by Barrell and is applicable to both the unlimited and limited types. When such crack fillings become exposed to observation, the mud layer is often no longer to be seen, as it is much softer than the filling material and may be quickly removed. Under very favorable circumstances, the curled laminæ may be preserved along with the filled crack. Such a case is illustrated by figure 15, where the top of the formation is obviously on the upper side. Where crack and filling can be seen in cross section, this condition offers a very positive means of determining top and bottom.

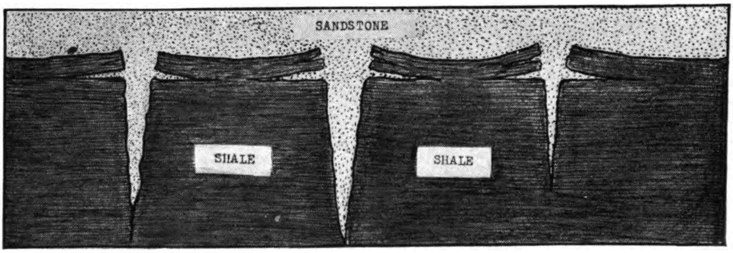

Fig. 15.

Ideal section showing "unlimited" mud cracks with curled laminae and fillings preserved.

Where the curled laminæ have been preserved but have been eroded out before observation, the direction of the curvature may frequently be noted in the intercrack area. In the case of the younger bed, the area between the cracks is usually convex, being the impression of the concave clay surface. As shown by figure 17,a the top is toward the left. This will be equally true of the limited and unlimited types of cracks.

In the case of limited cracks, it may happen that the entire thickness of the mud bed may curl away from the underlying sand. (Fig. 16.) If this space below the mud layer becomes filled with the same material which fills the

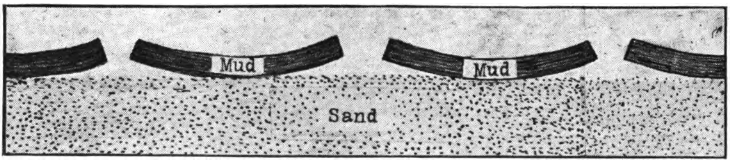

Fig. 16.

Ideal section of "limited" mud cracks before burial showing sublaminal openings, the fillings of which would produce the condition shown in figure 17, b.

crack, the curvature of the laminæ may also be preserved in the older sandstone layer. Upon later exposure and removal of the mud, the older bed will show concave inter-crack areas. In figure 17,b the top is toward the left.

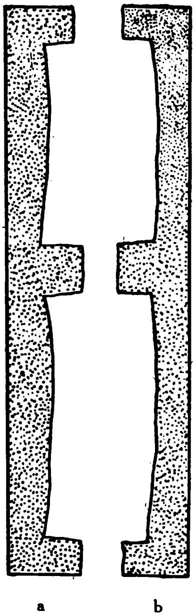

Fig. 17.
Section showing curvature of inter-crack areas due to impression of curled laminate on (a) younger bed, and fillings adhering to it; and (b) older bed, and fillings adhering to it.

But it may also happen that the clay crumbles down sufficiently so that there is no space left to be filled below the laminæ, as there was in the case of figure 16, or that the beds never curled sufficiently to form an opening below. If so, the inter-crack areas of the older bed will show no curvature whatever, and the case will be indeterminate. This results from the possibility that the inter-crack areas on the younger bed may also be flat in instances when the cracks were not accompanied by much curling of the mud. It is believed, however, that the inter-crack areas on the older beds will at most show only a very slight and irregular convexity.

In studying the application of the above to the limited type of mud cracks, careful search was made by means of quarrying off slabs of sandstone in areas where such cracks were known to be abundant, but no print of the upper surface of the mud layer was found in place. A study of some 360 specimens, all of which were in place in undisturbed beds in localities separated by a number of miles, showed 250 cases in which the surfaces between the projecting mud crack fillings were flat or slightly concave, about 1000 with well marked concavity, and 10 with a very slight but irregular convexity. These, of course, all represent the original upper surface of the older bed, and the lack of convex surfaces is corroborative of the view just presented. A large majority of the loose slabs, which probably came from the younger or originally overlying bed, showed convex inter-crack areas.

In further confirmation of this, a number of the slabs with convex inter-crack areas show minor narrow ridges, less prominent than the larger ones, which are believed to represent the fillings of small unlimited cracks which did not penetrate the entire thickness of the mud layer and which, therefore, mark the original bottom of the overlying younger layer. A further corroboration may sometimes be secured by considering the curvature of the thin septæ which adhere to the fillings, and which probably themselves are the filling of the horizontal openings between successive laminæ. Where enough of any septum is preserved to show curvature, the curvature has been found to conform to that of the inter-crack area.

Wedge shape.—It has been supposed that the gradual narrowing of mud cracks with depth so that in cross-section any individual crack is wedge-shaped, has been among the more important criteria for the recognition of the top and bottom of beds (Fig. 14). If both the cracked shale and the filling are preserved together and seen in cross-section, it is, of course, perfectly obvious which side was originally the top and which the bottom, no matter in which position the specimen is held.

This evidence has been cited by Barrell, and has been brought out but not applied by Gilbert,* who remarks: "On the northern flank of Mt. Ellsworth are the vestiges of a system of mud cracks, such as formed where wet clays are dried in the sun—tapering fillets of sand can be traced—downward ten feet into the clay." Figure 14, taken from Gilbert's report, illustrates the point.

Mr. Radcliffe** points out that this criterion is indeterminate in the case of the limited type of mud cracks, because the mud layers were evidently so thin that the cracks maintained the same width from top to bottom. If only a small portion of the filling were seen, the wedge-shape might not be recognizable and even the unlimited type of crack be indeterminate.

Irregular depth.—Where the thickness of the mud layer is such that the depth of the cracks have not been limited by its thickness, closely adjacent fractures will extend to unequal depths, although they all terminate above at the same general horizon, i. e., against the bed deposited above the cracked surface. (Fig. 14.) Although irregular depth is a characteristic feature of mud cracks, it has but little value in the determination of top and bottom of beds, since in

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*Loc. cit.
**Op. cit.

order for it to be visible, in all probability sufficient portions of the cracks must be seen to enable one to note also the wedge-shape of the cracks, a more direct criterion. It may, however, be of some confirmatory help. Naturally this criterion is not applicable to the limited type of mud cracks.

Summary.—The fact that mud cracks are found only in sediments of continental or literal origin indicates the small proportion of strata in which they can occur. Lack of proper conditions for their formation, imperfect preservation, destruction during orogenic disturbances, and the normal uncertainties of interpretation already discussed unite to limit the use of these criteria in the determination of the structural attitude of beds. Where mud cracks are found, structural determinations can usually be made if the observer keeps in mind the criteria outlined above; and it seems probable that the number of cases in which they are used will be considerably increased.

VARIATIONS IN SIZE OF GRAIN.

Among original structures used to determine the structural attitude of beds, variation in coarseness of grain has recently been suggested as of importance. Leith* says: "It is very common to find a diminution in coarseness of beds from the bottom toward the top. Even in microscopic sections this is aparent. The beds may start in abruptly with coarse sediments. These gradually become finer-grained above, and the next bed starts in again abruptly with coarser sediments. There is little difficulty in these cases, no matter what the folding, in determining the original top and bottom of beds. This has been found especially useful in interpreting drill samples from folded rocks.

In figure 18 the texture of each layer would be supposed to be more coarse towards its base, the sudden transition being from the finer upper portion of the older layer to the coarser lower portion of the younger layer.

So far as the writers know, this criterion was first applied in work in the Florence District in northern Wisconsin, under the direction of the State Geologist, W. O. Hotchkiss. At that time the junior author of this paper made a large number of observations of banded slates from which numerous samples were taken and oriented slides cut.

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*Leith, C. K., Structural geology, 1913, p. 132.

The evidence proved to be more or less contradictory, or at least indeterminate. In a personal communication Mr. Hotchkiss sums up the results he has obtained in the statement: "I do not believe much dependence is to be placed upon gradation of grain, except by observation of a great many cases."

In order to determine just how this supposer variation in size of grain might be developed, the writers performed the following simple experiment: Into a beaker, about 3 inches in diameter and 10 or 12 inches deep, about half filled with water, was slowly poured a small volume of sediment. In the first experiment a mixed sand and clay was used, all of which passed a 20-mesh sieve, and about 15 per cent of which passed a 200-mesh. After pouring in the first portion of the sand, the beaker was allowed to stand about five minutes until all but the very finest material had settled out. There was a distinct gradation in the layer of sediment formed, with the coarser grains at the bottom and the finer ones at the top. It could be noted, however, that the degree of assortment was far more complete in the finer than in the coarser portion. There seemed to be a size of particle all fragments larger than which came down as an unassorted mass. Below this size the rate of settling was sufficiently differential so that assortment was far more complete; sufficiently complete in fact to be easily detected with the naked eye.

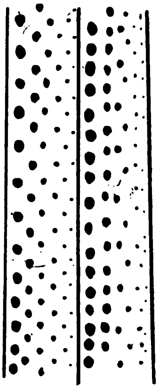

Fig. 18. Hypothetical section to show supposed change in size of grains in sedimentary beds.

After settling was reasonably complete, another portion of sediment was added and the process repeated till there were a number of layers in the beaker. The quantity was varied somewhat to give variation to the thickness of the layers produced. Each portion was poured in as quietly as possible in order not to disturb the water and not to stir up the layer of underlying sediment. It was found, however, that the surface became disturbed, in spite of all precautions, and that the coarser particles settling out mixed with the fine top of the earlier layer. This mixing was so extreme that the gradation was largely destroyed, and there was practically as intimate an intermingling of coarse and fine grains at the top as at the bottom of any given layer. A very careful study of the resulting pile of strata led to the conclusion that a determination of top and bottom was practically impossible. Another case was tried with coarser sediment, the material of which passed the 10-mesh and was retained on the 100-mesh screen. The variation was so indefinite as to be quite indeterminate.

These experiments, while they do not invalidate the principle involved in the criterion as stated, seem to substantiate the conclusion reached by Hotchkiss that only by using a very large number of observations could any very definite conclusion be reached. It is probably true, however, that where there is a definite gradation from coarse to fine in the same direction in several successive layers, it constitutes sufficient evidence of top and bottom. But such cases are probably extremely rare.

AMYGDULES AND SCORIACEOUS SURFACES.

Extrusive sheets of lava flows are usually characterized by amygdules and scoriaceous surfaces, which, as a rule, are developed more abundantly at the top than along the lower surface of the flow. It is certainly to be presumed that if they are much more abundant along one side of a flow than along the other, the side where they are most prominent was originally the top of the flow. If the beds were ultimately folded this feature might be of service in determining that fact. Clements* has already called attention to this criterion.

CLEAVAGES AND FRACTURES.

The subject of cleavage has been studied by many, a list of the names of whom, together with the results accomplished, are given by Leith.** Cleavage has been so variously defined, classified and named, that the following definitions (after Leith) are given in order that there can be no doubt as to their meaning in this paper:

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*Clements, J. M., The Crystal Falls iron bearing district of Michigan; Nineteenth Ann. Rept., U. S. Geol. Survey, Pt. 3, 1899, p. 54.

**Leith, C. K., Bull. U. S. Geol. Survey No. 239, 1905.

- Cleavage
  - Original
    - Flow
  - Secondary
    - Flow
    - Fracture

Cleavage is a rock structure by virtue of which the rock has a capacity to part along certain parellel surfaces more easily than along others.

Original cleavage is that which is induced in the rock mainly during its solidification from a magma or its deposition in water, though perhaps modified by subsequent static metamorphism.

Secondary cleavage is that which is induced by deformation through metamorphic processes subsequent to the formation of the rock.

Flow cleavage is that which is dependent on the parallel arrangement of the mineral constituents of the rock.

Fracture cleavage is that which depends for its existence on the development of incipient fractures, or actual fractures, which by subsequent welding or cementation remain plains of weakness.

In the determination of the structural position of beds we are here concerned only with the relation of bedding to secondary structures, and chiefly to its relation to secondary flow cleavage.

Flow cleavage.—When rocks are bent and folds created by tangential forces, the incompetent formations of the shale family tend to develop a secondary flow cleavage, the direction of which bears a definite relation to the resultant force at the point at that time, and to the bedding. As the fold rises, the weight of the superimposed formations is removed from the beds of the central portion of the fold to the limbs, so that there may even be a tendency to create openings between the beds at the crests and troughs of the folds. Meanwhile the beds become less and less nearly parallel to the deforming force which compresses the limbs and results in an actual flow of plastic material towards the low pressure areas of the crests and troughs. Inasmuch as in folding each bed in the limbs moves upward with respect to the bed below, the result is not one of simple compression, but of compression with rotation or "scission." In the crests and

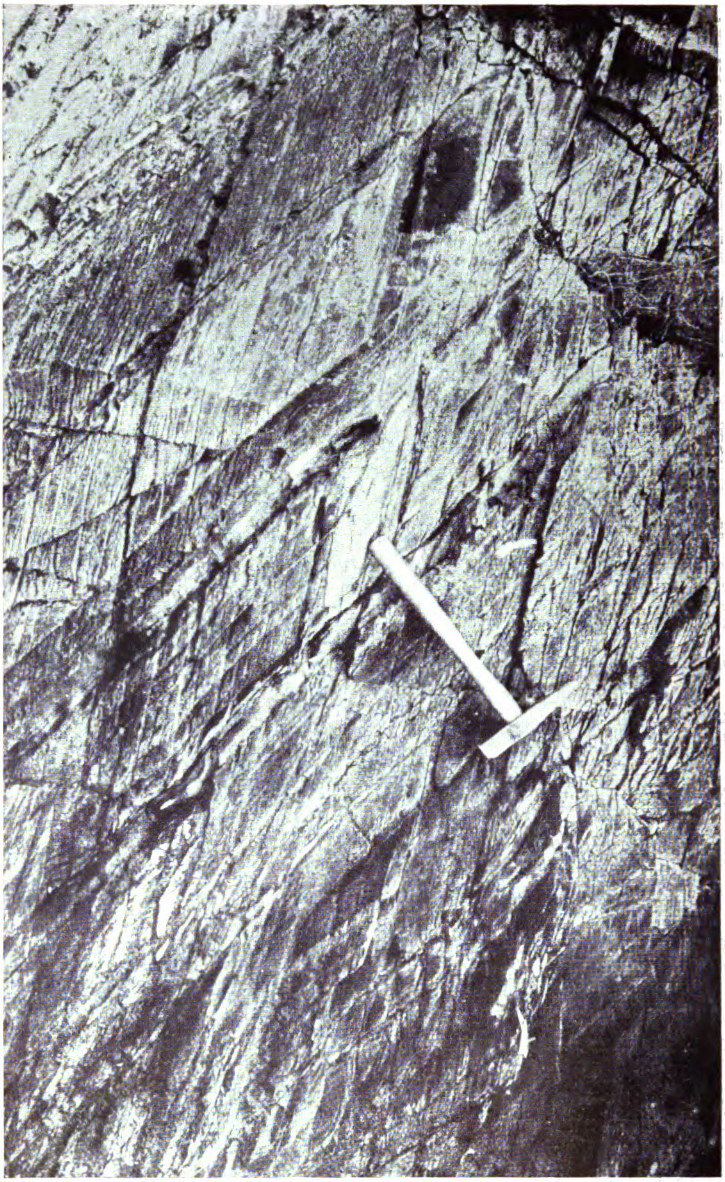

PLATE XVIII.
Bedding and secondary flow cleavage in slate. Wadebridge, Cornwall. (Lake and Rastall.)

troughs there is no differential movement of the beds, the compression is simple, and the resulting elongation parallel to the axial plane and normal to the beds. The direction of movement at any point and time is parallel to the elongation which, in the case of a nonrotational strain, is normal to the deforming force, and in the case of a rotational strain or "scission" is approximately at forty-five degrees to the bedding, line FE of figure 21.

Members of the shale family (it is chiefly these which develop secondary cleavages which can be used for structural determinations) are composed largely of minerals such as kaolinite, chlorite, micas, etc., two dimensions of which are much greater than the third, consequently at any point where a plastic flow takes place, such minerals will tend to arrange themselves with their greater dimensions parallel to the direction of movement. New minerals better adapted to the changed conditions of heat and pressure may be developed, while those which are stable may be changed in shape and enlarged. In such cases the directions of greatest dimensional development are in the lines of easiest relief, i. e., parallel to the direction of flow at that point. The concentration of movement at the contacts of the beds often results in an appreciable amount of drag and the formation of an S-shaped cleavage.

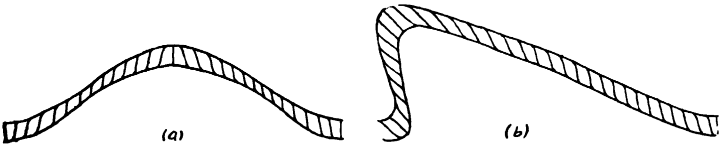

Fig 19.

Ideal section showing relation of secondary flow cleavage to bedding in (a) a low, simple fold, and (b) an overturned fold.

Leith shows that the resultants of the forces active in folding are such as to tend to produce secondary flow cleavage, as shown in figure 19,a. In the limbs of a low, simple fold the secondary flow cleavage will dip in the same direction as the beds, but at a greater angle, while at the crests and troughs it will be approximately normal to the bedding. The relation of the cleavage to the bedding planes in other positions of the fold can be quickly approximated by revolving the bedding and cleavage of a low, simple fold into the desired position. Thus in figure 29,b the left limb is shown to be overturned both by the bedding and cleavage and by the drag. The cleavage dips in the same direction as the beds, but at a smaller angle; hence the bed is overturned. The drag or S-shape of the cleavage shows that the outer bed on each limb has moved upward with respect to the inner, and is therefore stratigraphically above it.

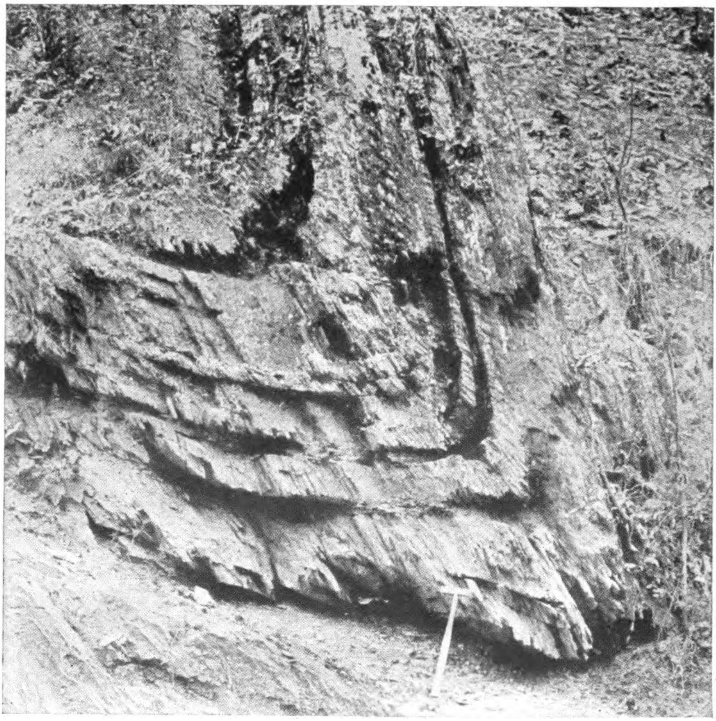

Fig. 20.

Slate showing the relation of secondary flow cleavage to bedding. Two miles south of Walland, Tenn. (U. S. Geol. Survey).

Fracture cleavage.—Strata which do not yield to stress by flowing, and which do not have or do not develop minerals of rather marked dimensional differences, do not develop good flow cleavages. They may, however, when in their zone of rock fracture, as defined by Van Hise,* yield by fracturing and so develop secondary structures of this nature. Tension joints are soldom, if ever, of any value in structural determinations. Compression joints resulting from "scission" may be used to a limited extent after the manner of secondary flow cleavage: The stresses in these beds are the same as outlined above, as is also the tendency on any portion of the mass to be elongated in a direction at approximately forty-five degrees to the bedding.

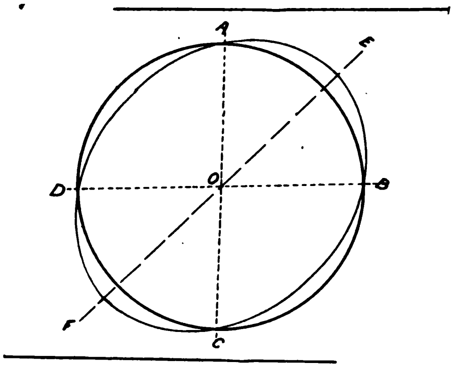

Fig. 21.

Sketch showing the relations under which fracture and secondary flow cleavage are developed.

A sphere or material before and after distortion is shown in figure 21. The material within the angles AOB and DOC tends to move outward, while that within the angles AOD and BOC moves inward, a condition resulting in a shearing action and the development of fracture and fracture cleavages along the lines of no distortion, AC and DB. Where the compression has been sufficient to cause fractures, the original sphere of material will usually have undergone more compression than shown in figure 21, and the angle AOB will be less than 90°. The fractures parallel to the line AC will be more abundant than those parallel to DB, because the former direction is more nearly normal to the force which finds less relief along a fracture in this direction, and because the latter is nearly parallel to the bedding so that it may be obscured or prevented by a yielding along bedding planes. Fractures and cleavage when developed in the above manner will dip more steeply than the flow cleavage and can be used in the same manner, but not with the same degree of certainty. (Fig. 22.)

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*Van Hise, C. R., Sixteenth Ann. Rept., U. S. Geol. Survey Pt. 1, 1896, p. 589.

Major fractures tend to occupy vertical positions irrespective of structure and are of no value in its interpretation. It is to a small portion of those fractures, which are limited in depth to a single bed, that this interpretation applies.

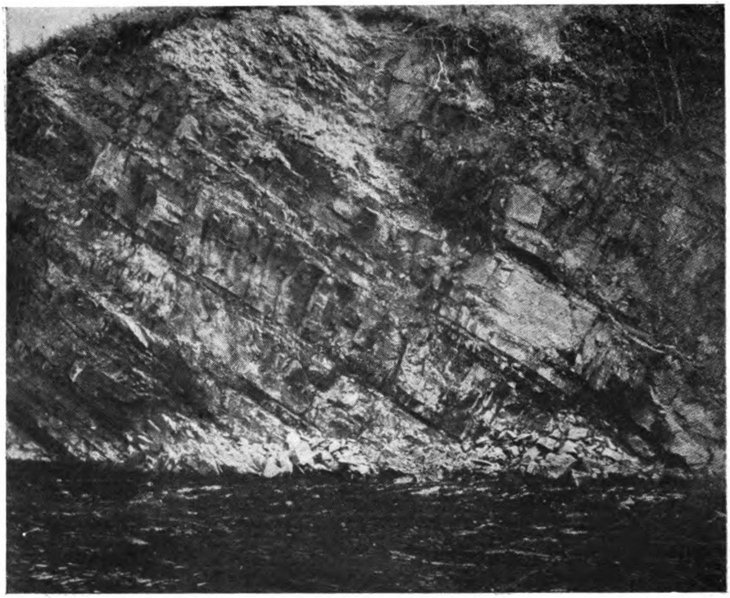

Fig. 22.

View showing relation of fractures to bedding in standstone and shales of Shaktolik River, Alaska. (U. S. Geol. Survey.)

Summary.—In reality the relation of secondary cleavage to bedding and the S-shape of the former show the direction in which one bed has moved with respect to the one above and the one below, consequently anything, such as a fault or slump, which produces a movement parallel to the bedding plane may create this condition and a false interpretatoin of structure may result. Such a condition would be of rare occurrence, and so far as we are aware, has been reported from but one place.

Secondary cleavages can thus be used in the determination of the structural positions of strata, and while the use of fracture cleavage is limited and at best is only an indication of the probable structural position, the relation of well developed secondary flow cleavage to the bedding can be considered as almost positive evidence.

CONCLUSION.

It is recognized that many minor criteria, such as stalactites and stalagmites, mica on the crests of ripple marks*, etc., have been omitted, they being too rare of application to warrant discussion. Doubtless some important criteria have also been omitted; but it is hoped that this bulletin will be of assistance to those interested in structural geology, and that it will be an incentive to those knowing other evidence of this nature to present it to the public in order that all may obtain better results in field work.

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*Woodworth, J. B., American Geologist, Vol. 27, 1901, p. 218.

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